Meteorological Conditions Associated with Hillslope Failures on the Queen Charlotte Islands

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FISH/FORESTRY INTERACTION PROGRAM

This study was undertaken as part of the Fish/Forestry Interaction Program (FFIP), a multidisciplinary research study initiated in 1981. The program was started following a series of major winter storms in 1978 that triggered landslides over much of the Queen Charlotte Islands' forest land base. Originating on steep slopes, many slides deposited tonnes of debris in streams and on valley flats. The events raised private and public concerns over logging practices on the Islands and prompted the establishment of the 5-year program. Overall objectives of FFIP were:

- to study the extent and severity of mass wasting and to assess its impacts on fish habitat and forest sites;
- to investigate the feasibility of rehabilitating stream and forest sites damaged by landslides;
- to assess alternative silvicultural treatments for maintaining and improving slope stability; and
- to investigate the feasibility and success of using alternative logging methods, including skylines and helicopters, and by logging planning to reduce logging-related failures.

The program is jointly funded by direct appropriations from the Canada Department of Fisheries and Oceans, the B.C. Ministry of Forests (Forest Science Research Branch), and the B.C. Ministry of Environment (Fisheries Branch). Participating agencies include Forestry Canada (Pacific Forestry Centre), and the Forest Engineering Research Institute of Canada (FERIC), Vancouver, B.C.

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For information about the program contact Ministry of Forests, Forest Science Research Branch, 31 Bastion Square, Victoria, B.C. V8W 3E7.

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SUMMARY

Heavy rainfall events are regularly associated with mass wasting on the Queen Charlotte Islands. We examined rainfall characteristics before and during verified slope failures in five geographic regions. The temporal frequency of these slope failures was compared with plots of cumulative departures from mean precipitation trends for antecedent time scales ranging from years to days.

Over the longer temporal scale, we found a positive correlation between **annual** moisture conditions and reported slope failure frequency. Over shorter time periods, only those **months** immediately preceding the slope failure appeared to be most important in conditioning the hillslope for failure. **Daily** antecedent conditions influenced how important variable amounts of short-term precipitation would be in triggering slope failures. Under wet antecedent daily conditions, slope failures were unlikely if the amount of precipitation received was less than 22 mm in a 24-hr period. More precipitation (29 mm/24 hr) was required to trigger landslides under dry antecedent conditions.

The limiting curves for wet and dry conditions merge when the precipitation event exceeds 2 days. The separation between limiting curves represents the amount of precipitation required before antecedent conditions become unimportant to slope failure occurrence. Storms with recurrence intervals of greater than 2 years were found to trigger failures regardless of antecedent moisture status.

Precipitation levels sufficient to trigger hillslope failures do occur at all times and in all areas of the Queen Charlotte Islands. Antecedent conditions are particularly important during the low magnitude-high frequency storms. When critical soil moisture-precipitation conditions are reached, forest harvesting activities in steep areas should be stopped to prevent failures at sensitive sites.

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1. INTRODUCTION

1.1 Background

Landslides are a common occurrence on the steep hillslopes of the Queen Charlotte Islands. Gimbarzevsky (1988) identified over 8000 events on recent air photographs. These landslides occur in a variety of forms, including debris slides, avalanches, flows, and torrents, and they can extend downslope into lower gradient areas of highly productive forest lands (Schwab 1986). In cases where slide material enters a stream channel, the morphological nature of the channel may be severely altered (Hogan 1986) and valuable fish habitats are damaged or destroyed (Tripp and Poulin 1986).

The causes associated with each type of failure are complex and highly variable. Factors that commonly contribute to failure include: geologic-topographic setting and seismic activity (Sutherland Brown 1968; Alley and Thomson 1978); land-use practices (Wilford and Schwab 1982; Rood 1985; Krag *et al.* 1986), and precipitation conditions (Schwab 1983). However, only precipitation is cited in most slope failure cases reported from the Queen Charlotte Islands.

The apparent link between heavy precipitation events and mass wasting has led some researchers to develop threshold models based solely on the intensity and duration of precipitation. For example, Caine (1980) compiled results from 73 studies and found that slides appear to occur when rainfall intensities exceed specific values. For example, his findings indicate that landslides may occur when intensities exceed 14.8 mm in a 1-hr period. However, Caine's relationship is not fully applicable to regional analysis, such as in the Queen Charlotte Islands, because it incorporates many different climatic zones, diverse geologic and topographic environments, a complete range of antecedent moisture conditions, and inconsistent records. It is also restricted to unstable hillslope areas.

Innes (1983) refined Caine's (1980) work by restricting the data set to debris flows exclusively. The resultant limiting curve has the same general form as Caine's, but a considerably lower threshold value. For example, debris flows occurred when precipitation intensity exceeded 4.9 mm in a 1-hr period.

Many factors complicate the relationship between hillslope failures and precipitation, making the use of limit curves for prediction difficult. Sidle *et al.* (1985), for example, show that antecedent weather conditions are critical in the relationship between precipitation events and landslides. Neither the Innes nor the Caine model incorporates this factor. Church and Miles (1987) also stress the significance of meteorological antecedents to mass movement events. Their studies of several episodes of debris flows in southwestern British Columbia indicate that many debris flow events are associated with notable but not exceptional storms. The authors credited moisture conditions before the storm with establishing the site conditions conducive to failure. The antecedent conditions that determine whether a storm will generate debris flows appear to be rain amounts before the storm and the influence of condensation melt and freezing levels on the release of snowmelt waters.

Although most researchers conclude that no method which reliably predicts the occurrence of debris torrents is likely to be developed, they support the use of several diagnostic techniques (Sidle *et al.* 1985). Church and Miles (1986) point to the difficulties inherent in developing predictive models, but they suggest that it may "become possible to provide generalized forecasts of the potential occurrence of debris flows in torrent-prone areas based on incoming storm conditions." Sidle *et al.* (1985) agree that such forecasts are possible, particularly if antecedent moisture conditions are considered and if storm event return frequencies can be calculated for the geographic region.

Clearly then, weather is an important factor influencing the probability of slope failure. Forest management plans must take it into account. However, to consider this element effectively in the planning process, the meteorological conditions — particularly antecedents — associated with past failures for a given area must first be evaluated. Information on antecedent moisture conditions, used together with the precipitation intensity and duration/landslide occurrence graphs, should fill the gap evident in other studies and provide a useful method of showing the potential for hillslope failures. This approach may provide regional scale information to supplement site-specific terrain mapping methods now used to identify areas prone to slope failures (see, for example, Rollerson and Sondheim 1985).

1.2 Objectives

The objective of this study was to investigate and define the relationship between meteorological conditions and slope failure occurrences in the Queen Charlotte Islands. The specific steps taken were:

1. to compile a comprehensive list of observed slope failure locations and times of occurrence;
2. to document the meteorological conditions, both leading up to and during the event, associated with each inventoried slope failure; and
3. to investigate the threshold of occurrence for mass movements on the Queen Charlotte Islands by determining the relationship between meteorological conditions and the timing of slope failures.

The terms mass wasting, mass movement, landslide, and hillslope failure are often used interchangeably. In this report, "hillslope failure" or "slope failure" is used to describe debris flows, debris torrents, debris slides, and debris avalanches. In most cases, the type of mass wasting is not specified in field reports.

2. STUDY DESIGN AND METHODS

2.1 Slope Failure Inventory

The inventory of slope failure location and time of occurrence was compiled from information provided by the forest industry and government agency staff working on the Queen Charlotte Islands.[1] Only verifiable events were included. The type of slope failure was also noted when the information existed. The study locations were chosen primarily because slope failure data were available for forest development areas. The areas selected were Rennell Sound, Juskatla, Sewell Inlet, East Moresby and Skidegate Channel (Figure 1). In most cases the time of failure occurrence was assigned to the calendar day rather than to a specific hour, because the exact time was seldom documented.

The inventory includes hillslope failures that occurred on forested and clearcut slopes. We considered the conditions associated with each event, for example road failures, when developing relationships between precipitation and hillslope failure.

2.2 Meteorological Conditions

2.2.1 Study design

Meteorological conditions preceding and during selected storms were examined. Antecedent moisture conditions were evaluated at three temporal scales (Figure 2): yearly climatic trends, monthly precipitation patterns, and daily precipitation characteristics. Precipitation intensity and duration were evaluated for the storm associated with each hillslope failure.

2.2.2 Data sources

Precipitation data were obtained from the Canadian Atmospheric Environment Service (AES), and the B.C. Provincial Air Study Branch (previously referred to as the Resource Analysis Branch [RAB]). Precipitation data from the climate station that best represents the hillslope failure site (Table 1) was analyzed (most similar sites with respect to geographic setting, elevation, aspect, etc.). The climate station characteristics are detailed in Hogan and Schwab (1990). These data were available in daily total format for annual, monthly and daily trend analysis.

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[1] Inventory data were provided by Canadian Forest Service (Dr. R.B. Smith), MacMillan Bloedel Ltd. (Juskatla), Western Forest Product Ltd. (Sewell Inlet), Crown Forest Industries (Sandspit), B.C. Forest Service (Forest Sciences Section, Smithers and Queen Charlotte Islands District Office), and B.C. Ministry of Environment (Queen Charlotte City).

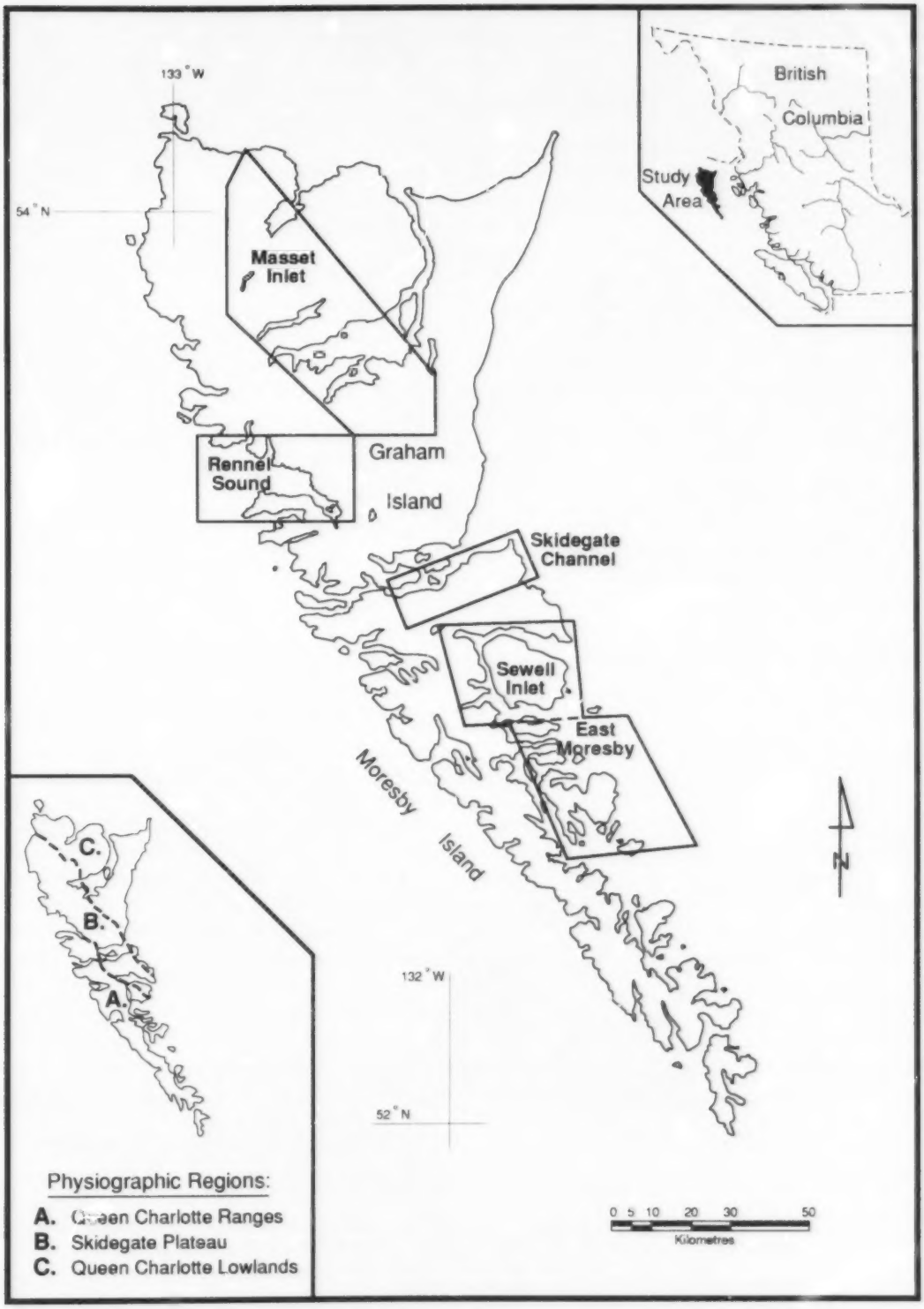

FIGURE 1. Location map showing selected study regions.

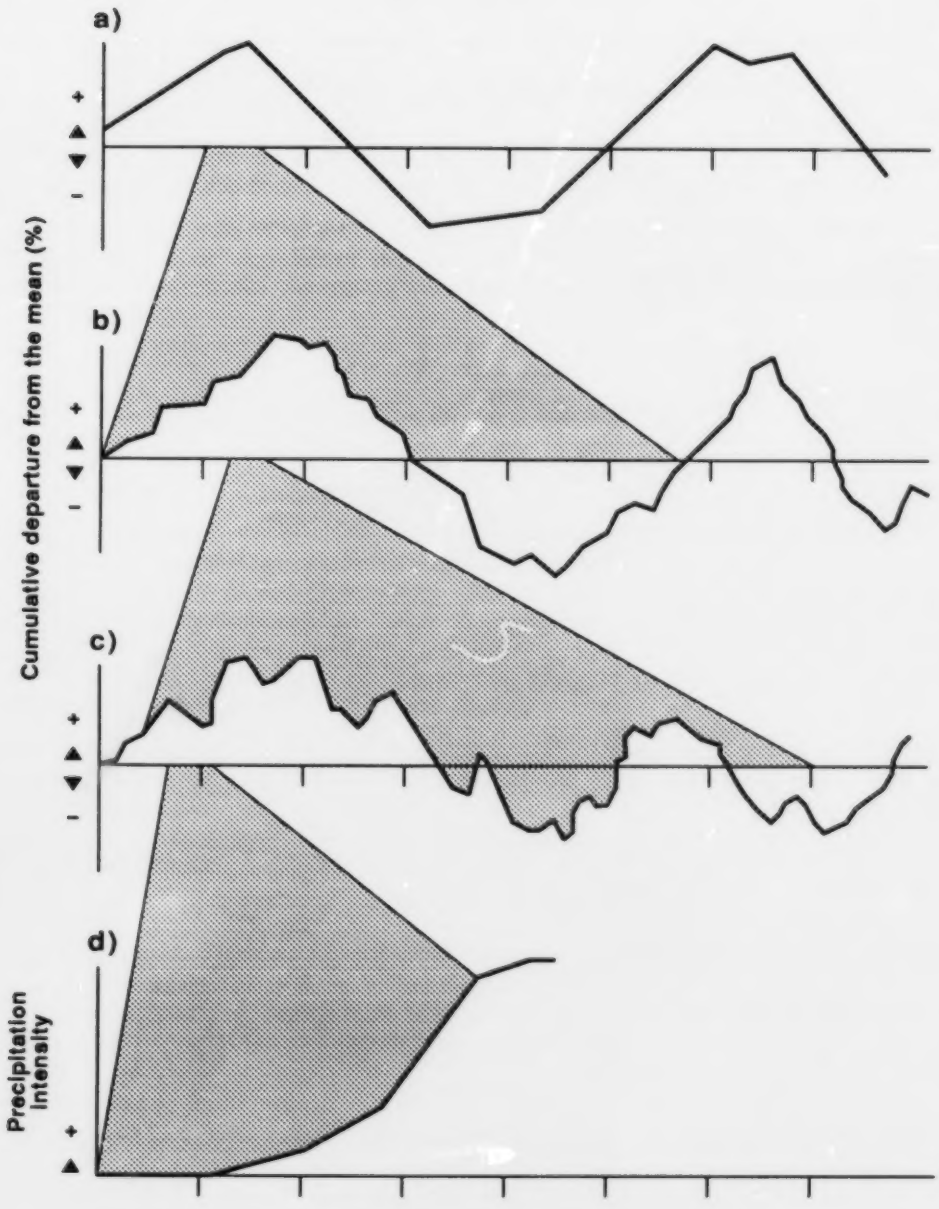

FIGURE 2. Method used to evaluate temporal aspects of antecedent moisture conditions in the Queen Charlotte Islands:

a) yearly (climatic) trends (from Karanka, 1986)
b) monthly precipitation patterns
c) daily precipitation patterns
d) storm precipitation intensities and durations

TABLE 1. Summary of study locations, areas included in each major region, and their most representative weather station[a]

Major study region	Areas included	Most representative weather station
Rennell Sound	Gregory Creek Bonanza Creek Riley Creek CIPA Camp Phantom Creek	Tasu (AES) Rennell Sound (AES) Gospel Point (RAB) Penthouse (RAB)
Sewell Inlet	Sewell Inlet Thorson Creek Newcombe Creek	Sewell Inlet (AES)
East Moresby	Louise Island (Mathers Ck) Lyell Island Burnaby Island Talunkwan Island	Sewell Inlet (AES)
Masset Inlet	Juskatla Dian Bay McClinton Bay	Sewall Masset Inlet (AES)
Skidegate Channel	Deena River South Bay Creek Alliford Bay Haans Creek Sachs Creek Sandspit area	Sandspit A (AES) Deena (RAB)

[a] See Hogan and Schwab (1990) for geographical details of each weather station.

All frequency analysis results were obtained from Hogan and Schwab (1990). Hourly data from Sandspit Airport (AES) and RAB stations were used for storm analyses. The difference in geographical setting between the weather station and the actual site of the reported hillslope failures is an important limitation in the present study, but rarely are site-specific weather data available for a particular event. The type of data used are generally all that exist for a given area. Air data (mean freezing levels) were obtained from the Port Hardy station (AES) and Annette Island in Alaska (USWS) for those periods suspected to be influenced by rain on snow events.

2.2.3 Analytical techniques

We examined the atmospheric moisture conditions during and preceding hillslope failure events. Moisture conditions were assessed relative to their long-term averages (as discussed below). The cumulative percent deviation curve technique (Buishand 1982; Karanka 1986) was used to show precipitation trends. The cumulative deviation, or departure, values were calculated as follows:

$$y_i = 100^{*} \sum_{i=1}^{j} ((x^i/\bar{x})-1)$$

where: y_i = cumulative percent departure from the mean to year i of record
x_i = the precipitation value for year i

and: $\bar{x}$ = the mean for period of record
j = years

The only data used were those shown by Karanka (1986) to be homogeneous with respect to station location, exposure, and instrumentation during the period.

The cumulative departure plots of Karanka (1986) were used to characterize the precipitation patterns on an annual basis. For the shorter time periods (months and days), the same cumulative departure from the mean technique was used. For monthly plots, the mean for each month was used and summed chronologically. For example, the August precipitation value was compared to the mean for August (based on the period of record) and the departure from the mean was added to the September departure (based on the mean for September).

The same procedure was followed for the daily values. The daily mean was calculated simply as the mean monthly value divided by the number of days in that month. Mean values for specific days of the year are not available for any of the Queen Charlotte Islands weather stations.

2.3 Meteorological Conditions — Slope Failure Relationship

The relationship between meteorological conditions and slope failures was developed in a manner similar to that used by Caine (1980) and Innes (1983). The threshold for hillslope instability is shown as a limiting curve which envelopes all data points. The complete data set was separated into two groups of slope failures: those that occurred with dry antecedent moisture conditions and those that occurred with wet antecedent conditions. The limiting curve was developed for each group.

3. REPORTED HILLSLOPE FAILURES

A total of 712 hillslope failures were reported for the five regions considered in this study during the 11 years from 1974 to 1984 (Appendix 1). The annual failure frequency is shown in Figure 3. Over 80% of all failures reported occurred during just 2 years (1978 and 1984) and the 1978 period was the most important. The inventory is thought to be relatively complete, though it only includes hillslope failures reported to government and industry personnel. The frequency values presented are, therefore, only minimum estimates. The 1980 and 1981 time periods are almost certainly underrepresented. Furthermore, the inventory does not consider failure magnitude. The historical distribution of hillslope failures on the Queen Charlotte Islands is being addressed in another study.[2]

The geographic distribution of reported landslides shows that the highest levels of hillslope activity are in the Rennell Sound and East Moresby Islands areas (Figure 4). Gimbarzevsky (1988) presents a far more complete spatial analysis of mass wasting on the Queen Charlotte Islands based on air photograph records. His results show that the Graham Ranges, which make up less than 15% of the total land area (Figure 5a) have the highest failure frequency (Figure 5b). Combined, the Graham and Moresby ranges have just less than one-half of all hillslope failures reported by Gimbarzevsky. Our Rennell Sound study area falls within the Graham Ranges physiographic region. The East Coast Mountains physiographic region has the third highest level of slope failure activity in Gimbarzevsky's data set; our East Coast Moresby area lies within this zone and has our second highest levels. The relative agreement between ours and Gimbarzevsky's spatial distribution data indicates that our inventory, although not absolutely comprehensive, is representative of the Queen Charlotte Islands.

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[2] Research project EP#782-07. Historical documentation of mass wasting in North Coastal British Columbia. J.W. Schwab, Forest Sciences Section, B.C. Forest Service, Smithers, B.C.

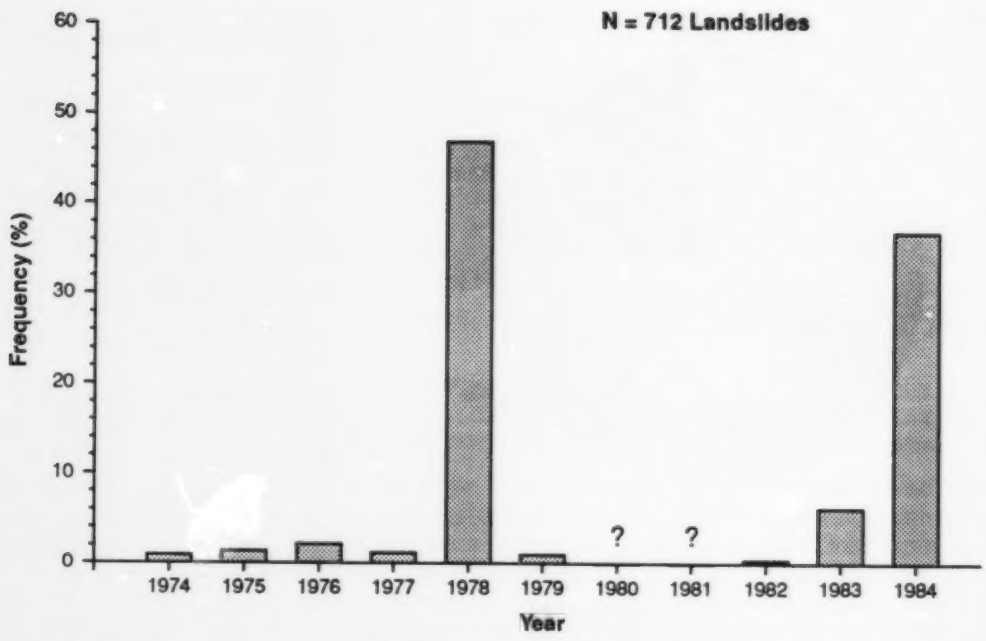


FIGURE 3. Total number of reported hillslope failures per year, 1974 - 1984.

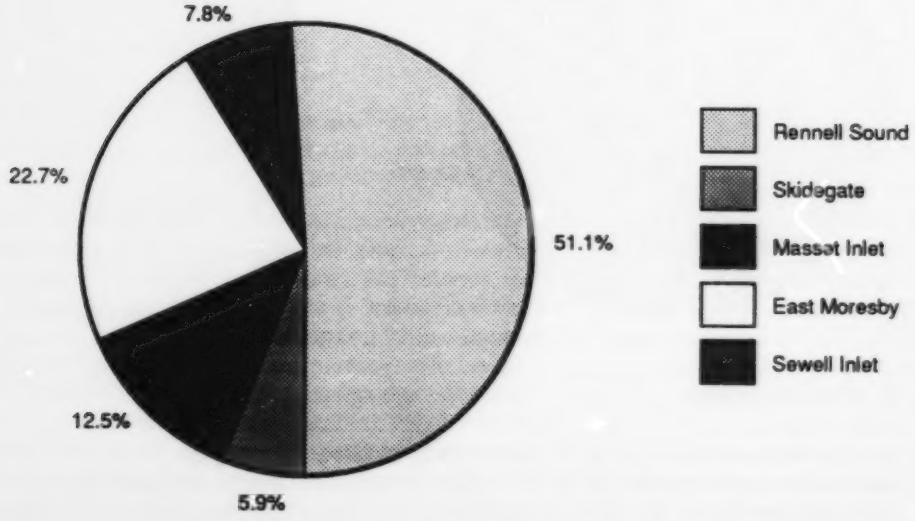
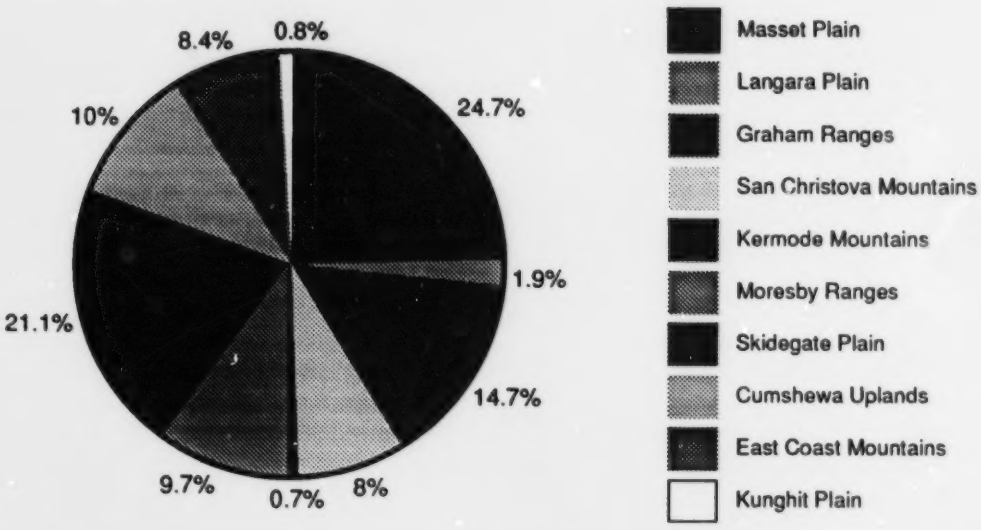


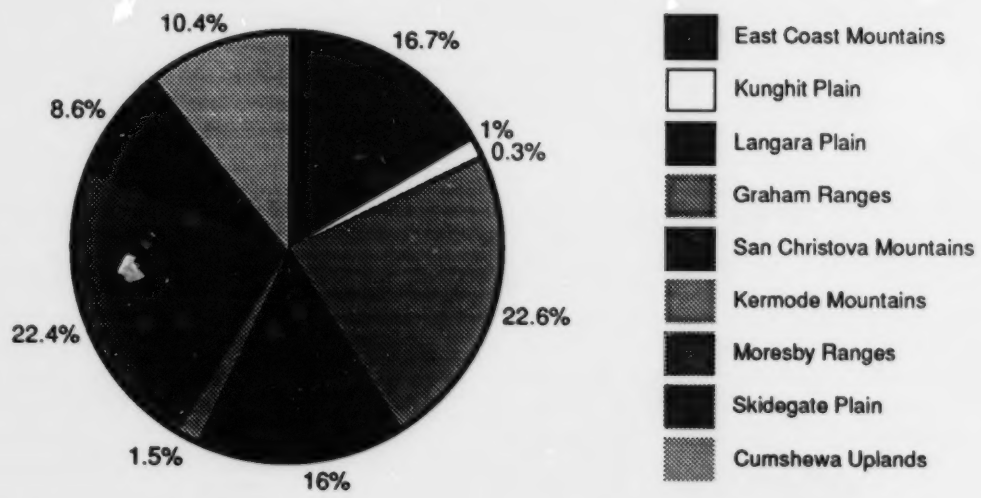
FIGURE 4. Geographic distribution of hillslope failures reported during the 1974 - 1984 period on the Queen Charlotte Islands.

a) Total land area per physiographic region



N = 9946 km²

b) Landslide frequency by physiographic region



N = 8238 landslides

FIGURE 5. Land base area and slope failure frequency by physiographic region (Gimbarzevsky 1988). Note that the Rennell Sound study area falls within the Graham Ranges, Masset Inlet is in the Skidegate Plain and Sewell Inlet, Skidegate Channel and East Coast Moresby are in the East Coast Mountain physiographic regions. The relative agreement between ours and Gimbarzevsky's spatial distribution data indicates that our inventory, although not absolutely comprehensive, is representative of the Queen Charlotte Islands.

4. ANTECEDENT PRECIPITATION — HILLSLOPE FAILURE PATTERNS

The relationship between precipitation and hillslope failures is investigated at four temporal scales; these include annual, monthly, daily and hourly time periods.

4.1 Annual Patterns

The annual moisture conditions of the Queen Charlotte Islands were investigated by Karanka (1986). His cumulative percent deviation from the mean graphs for precipitation are presented in Figure 6 and Appendix 1 along with our reported landslide events for the selected regions. The cumulative departure graphs provide an excellent representation of patterns in the data series. Periods of below, near, and above mean annual precipitation are shown as changes in the slope of the line. Periods of below mean precipitation have a negative slope (downwards to the right); periods of above mean precipitation have a positive slope (upwards to the right); periods of near mean precipitation have a zero slope. Points of change in the slope of the line indicate the timing of changes between wet and dry periods.

Long-term precipitation records presented by Karanka (1986) show that the Queen Charlotte Islands have experienced three time periods with above normal autumn and winter rainfall. These were 1923/24 to 1945/46, 1957/58 to 1963/64, and 1974/75 to 1983/84. The intervening periods had below normal precipitation amounts.

The annual cumulative precipitation and slope failure occurrence records are compared in Figure 6. Several patterns are evident. In all regions, the 1974 - 1984 time period appears to be wetter than the average. With the exception of Tasu, the latter years are the wettest. In most cases (Sewell Inlet is the exception), relatively frequent failure occurrences coincide with the shift from relatively dry to wet conditions. Also, many slope failures occur in all regions during the latter part of the period. These points indicate that there is a relation between precipitation and slope failure frequency: as annual precipitation increases with respect to the average after 1973, the number of failures also appears to increase.

However, there are shorter periods within the 11-year record that do not follow this pattern. For instance, lower than average precipitation, lasting from 1976 to 1978, coincided with a relatively large number of slope failures. The 1978 events are a good example. Conversely, there are periods with relatively high precipitation levels corresponding to low frequency of failures (e.g., 1979 - 1981). Therefore, although there appears to be a general pattern evident in the data, the minor discrepancies (high precipitation and few hillslope failures; and low precipitation and many hillslope failures) suggest that moisture conditions associated with shorter antecedent periods should be investigated.

4.2 Monthly Patterns

The monthly pattern of slope failures and mean monthly total precipitation is shown in Figure 7. The most important month for reported hillslope failures is October (Figure 7a); almost three times as many slides occur in October than in the second most prevalent month (November).

This period of high slope failure occurrence coincides with the wettest period of the year (Figure 7b), although failures do occur during all other seasons. **Total** precipitation appears to be only one of several moisture conditions that trigger slope failures. For instance, there is good agreement between high precipitation amounts and frequent slope failure events in October and November, but no agreement between the relatively high March and April precipitation amounts and the low slope failure frequency for these months. This suggests that the antecedent moisture conditions, particularly in the preceding months, and different types of storms are important to hillslope failure frequency because precipitation intensity varies with type of storm. Harvesting activities during the summer may also establish conditions conducive to hillslope failure, but landslides do not occur until the first significant rainfall, usually in October or November of the following year. Therefore, harvesting activities, in addition to meteorological conditions, probably set the stage for future hillslope failure.

The strong relationship between high monthly precipitation amounts and frequent hillslope failures (Figure 7) indicates that the shorter time periods are of more relevance to hillslope failure occurrence than are

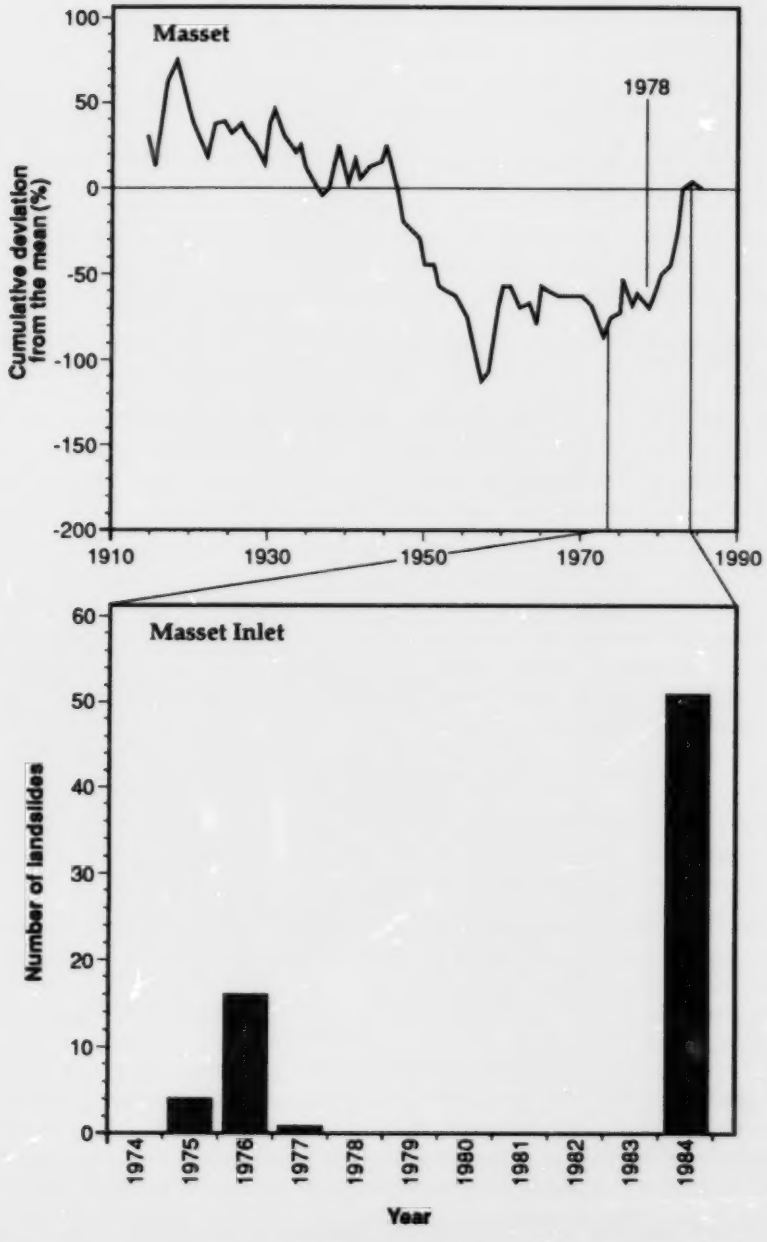


FIGURE 6. Cumulative percent deviation of October to April precipitation (from Karanka 1986) and reported hillslope failures by region.

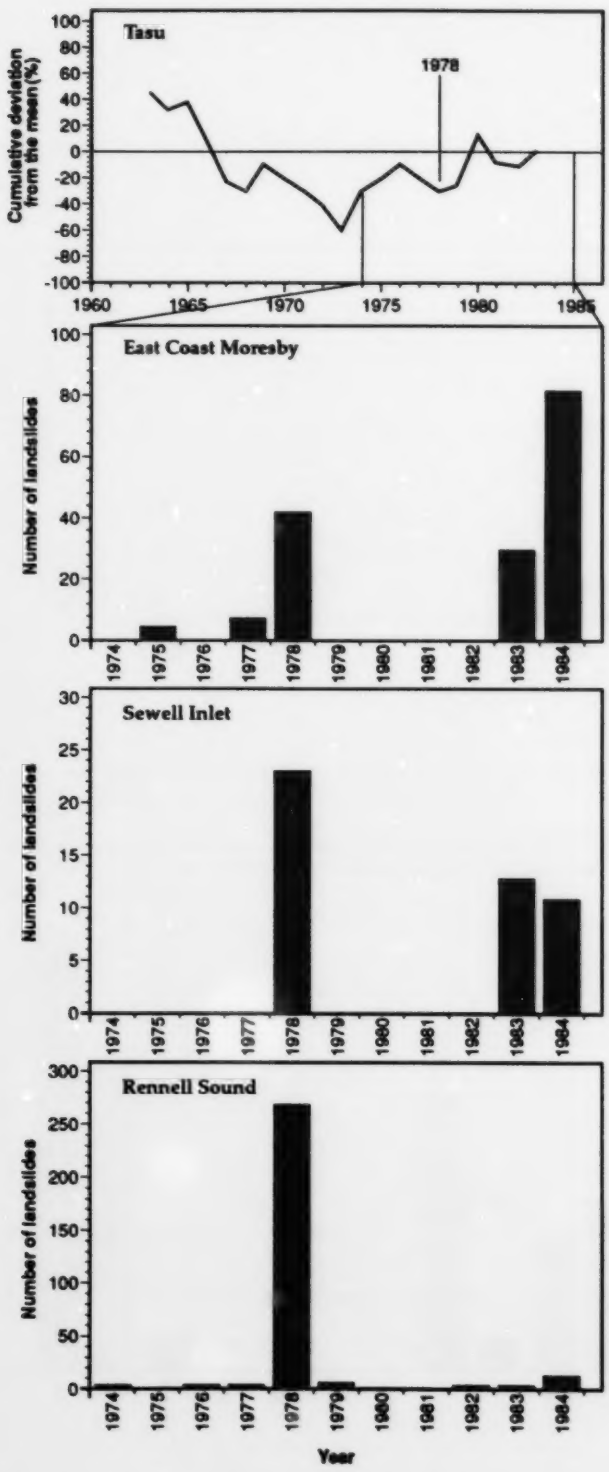


FIGURE 6. (Continued).

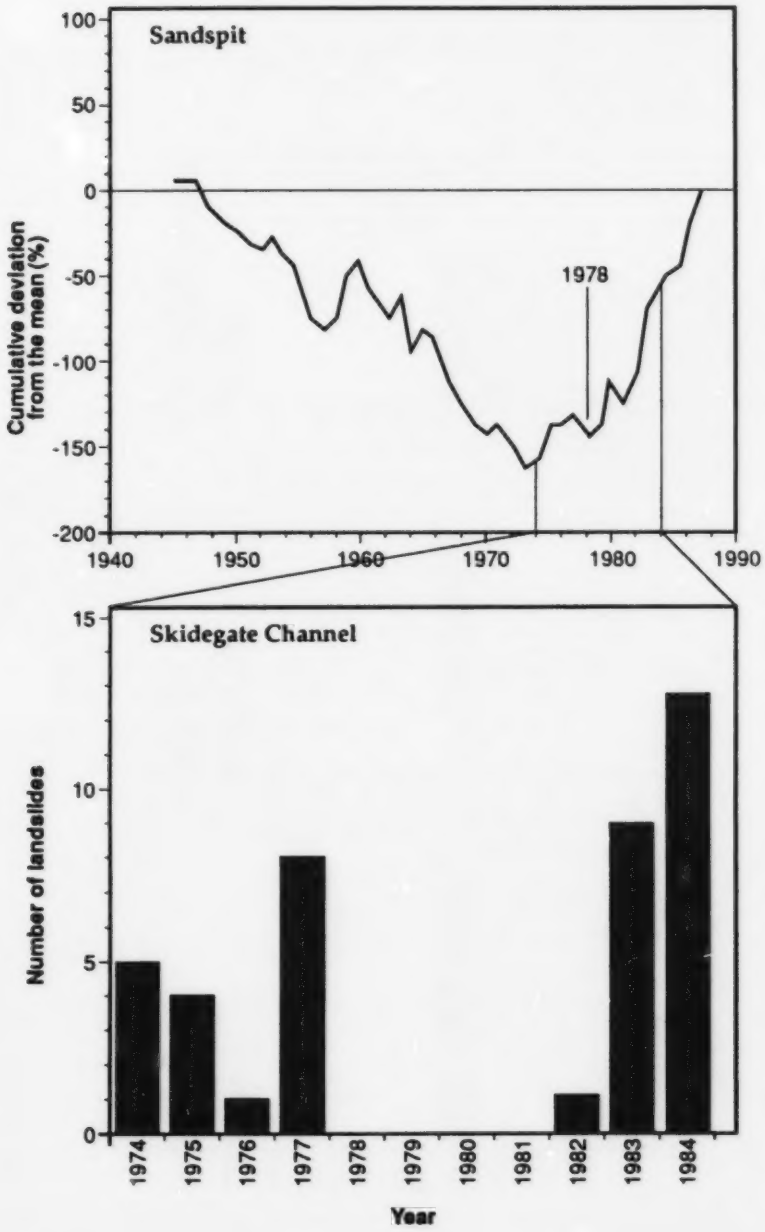
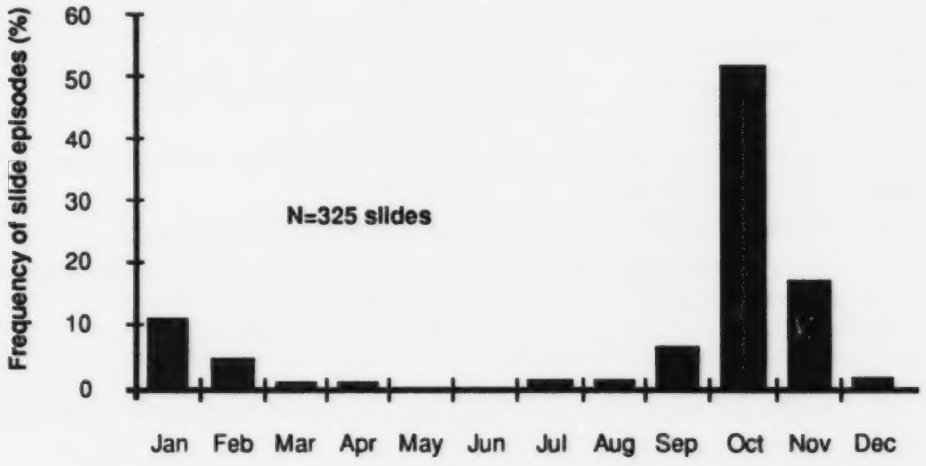


FIGURE 6. (Continued).

a) Slope failure frequency by month (1974-1984)



b) Total monthly precipitation (1950-1979 normals)

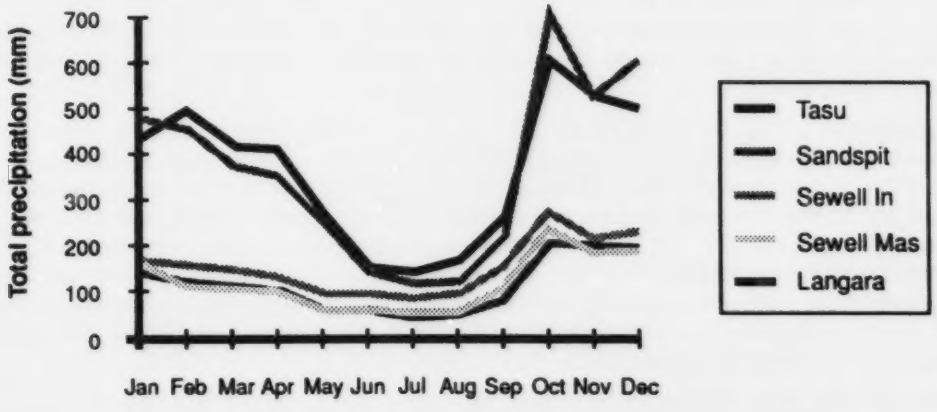


FIGURE 7. Reported hillslope failures and total precipitation events by month.

the annual moisture conditions. Cumulative departures from the mean monthly precipitation are plotted in Figure 8 and Appendix 2 to show the shorter term antecedent moisture conditions. These graphs are plotted in the same manner as the annual series and show the temporal extent of relatively wet and dry conditions occurring before hillslope failure.

Several antecedent moisture conditions are associated with slope failures. The monthly plots (Figure 8 and Appendix 2) show that the antecedent moisture conditions associated with hillslope failures are more complex than simply "wet" or "dry". We have selected four classes to summarize the antecedent conditions:

1. Wet: Both the preceding months (3 or more) and the month during which the slide occurred had above average precipitation.
2. Dry-to-wet: Only the month during which the slope failure occurred had above average precipitation levels and the preceding months were relatively dry.
3. Wet-to-dry: The slope failure month had below average precipitation but previous months had above average precipitation levels.
4. Dry: All months before and during the slope failure event had below average precipitation levels.

The frequency of reported slope failure occurrences associated with each class is summarized in Figure 9. When the results from all regions are combined (Figure 9a), most slope failures coincide with generally wet monthly conditions (Class 1). The second most common condition is associated with a moderate magnitude precipitation event that follows a period of wet weather. The third most frequently occurring condition (Class 2) is associated with precipitation events that follow prolonged dry periods. The regional plots display slightly different trends (Figure 9b). Class 2 is the most frequently occurring condition in Rennell Sound and the second most important situation in the Skidegate Channel and Sewell Inlet areas.

Several weather conditions appear to be important antecedents to hillslope failures on the Queen Charlottes. First, the most important situation, in terms of causing a high frequency of slope failures, is continual wet weather. Second, many failures occur when low precipitation amounts are received after extended periods of above normal precipitation (e.g., landslide numbers 49, 50 and 64 in Appendix 1). Third, many slides occur as a result of relatively moderate precipitation amounts received after prolonged periods of dry, below normal precipitation (e.g., landslide numbers 67-72 in Appendix 1).

4.3 Daily Patterns

Several weather conditions discussed above suggest that rainfall received over time periods shorter than months are important in contributing to landslide occurrence. Daily precipitation records were used to evaluate the reduced time scales. This analysis is based on the cumulative departure from the mean daily precipitation for each weather station.

Typical plots of the cumulative departure from the mean daily precipitation are presented in Figure 10. These are interpreted as follows: if on a daily basis it rains the mean amount, then the curve has a slope equal to zero and the 10-day cumulative total will equal zero; if it is completely dry, then the curve will have a negative slope and the 10-day cumulative total will equal -1000; if it rains twice the average, then the slope will be positive and the 10-day total will be +1000; if it rains three times the average, then the 10-day total will be +2000; and so on. Therefore, if the cumulative departure plot line is positive at the beginning of the storm event, then the antecedent days are classed as wet (Figure 10a). Conversely, if the line is negative at the beginning of the storm period, the preceding days are considered to be dry (Figure 10b). Larger cumulative departure values indicate the degree of "wetness" or "dryness".

All days preceding reported storm events have been assessed and plotted in the above manner. The 10-day cumulative departure values are listed in Table 2 and summarized in Figure 11. These show that slightly more slides occur after generally wet conditions are experienced than after dry antecedent conditions. As well, relatively few occurrences are associated with average moisture conditions (± 200 antecedent moisture index values).

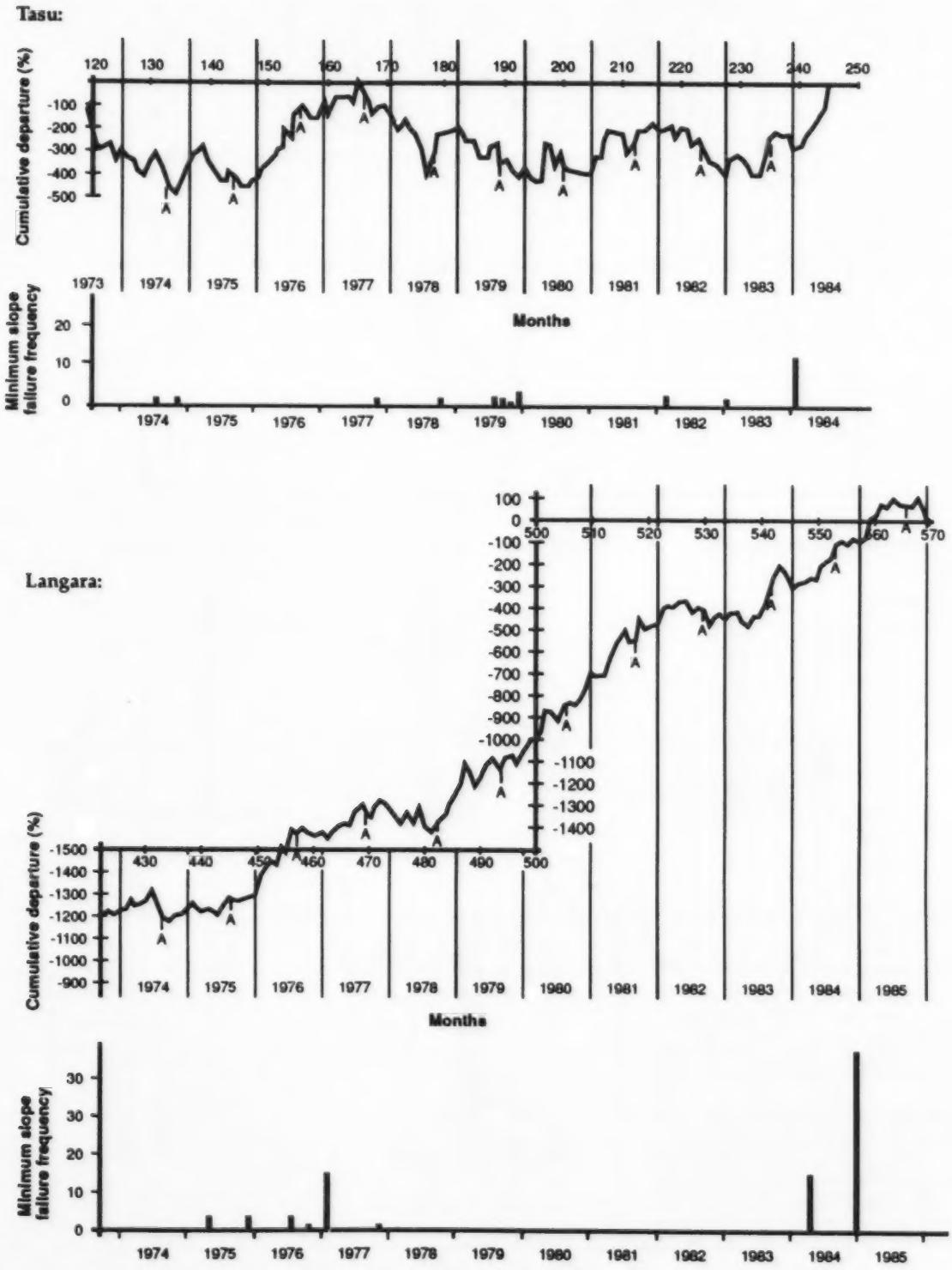
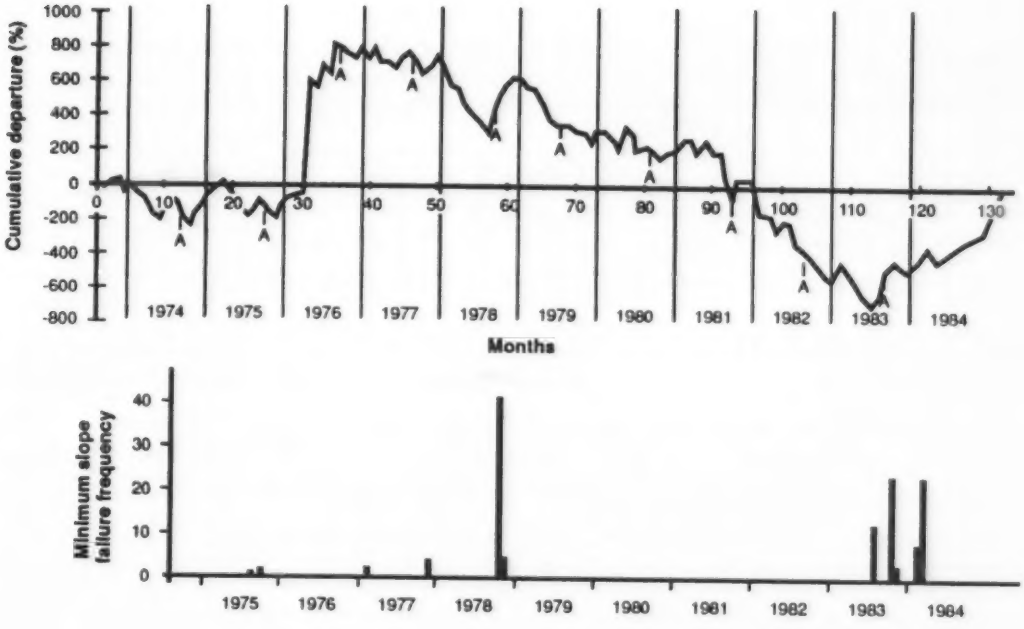


FIGURE 8. Cumulative departure from the monthly precipitation and reported hillslope failures by region. (Note that "A" indicates position of August in each series.)

Sewell Inlet:



Sandspit:

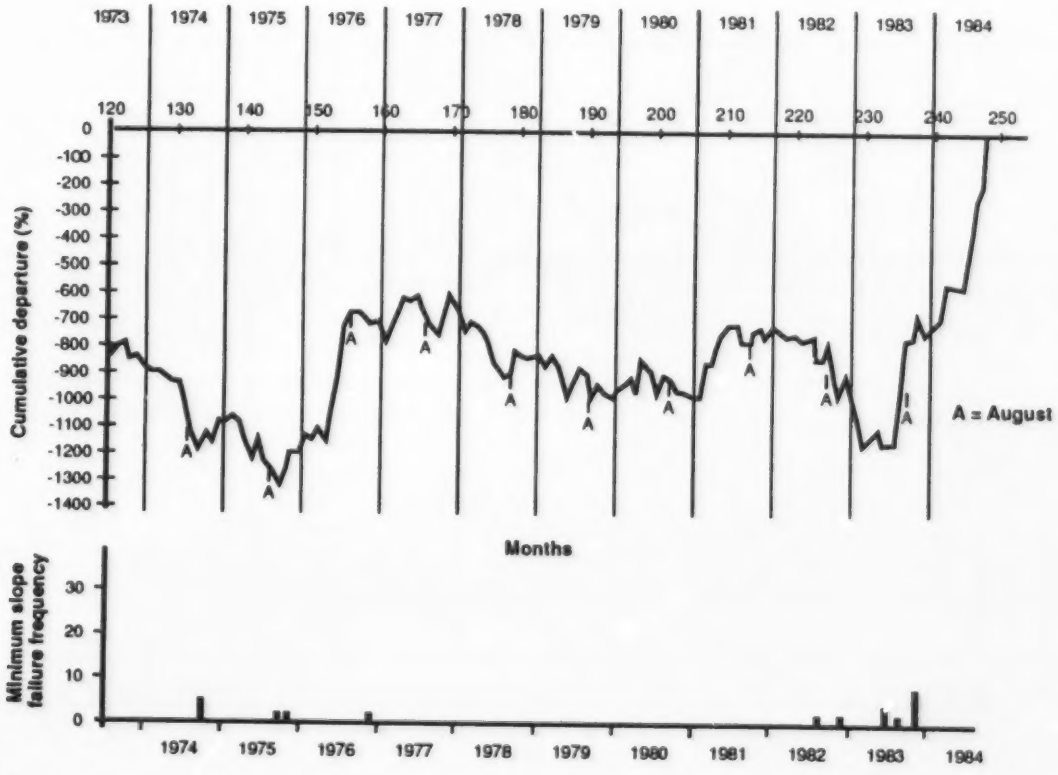


FIGURE 8. (Continued).

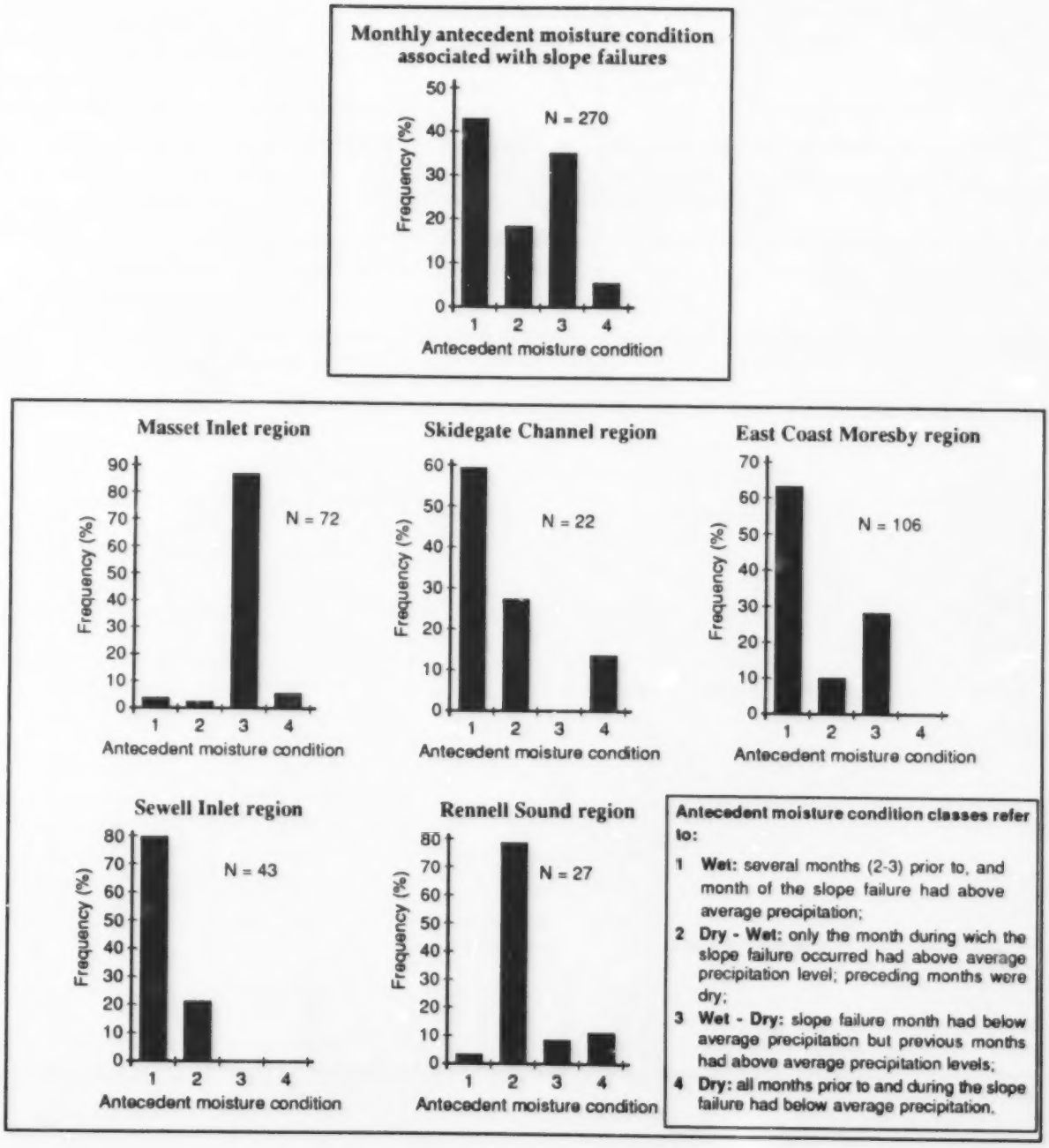
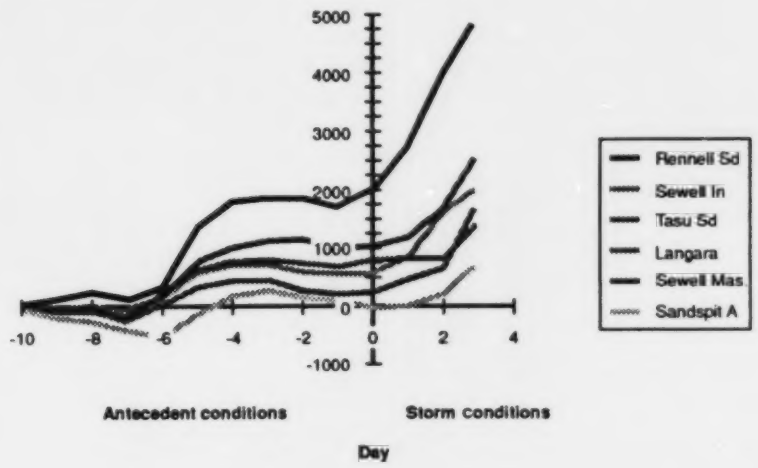

Monthly antecedent moisture condition associated with slope failures
N = 270
Frequency (%)
Antecedent moisture condition
Masset Inlet region
N = 72
Skidegate Channel region
N = 22
East Coast Moresby region
N = 106
Sewell Inlet region
N = 43
Rennell Sound region
N = 27
Antecedent moisture condition classes refer to:
1 Wet: several months (2-3) prior to, and month of the slope failure had above average precipitation;
2 Dry - Wet: only the month during wich the slope failure occurred had above average precipitation level; preceding months were dry;
3 Wet - Dry: slope failure month had below average precipitation but previous months had above average precipitation levels;
4 Dry: all months prior to and during the slope failure had below average precipitation.

FIGURE 9. Monthly antecedent moisture conditions associated with hillslope failures.

a) Daily moisture conditions, Sept. 25 to Oct. 8, 1974: WET



b) Daily moisture conditions, Sept. 19 to Oct. 2, 1974: DRY

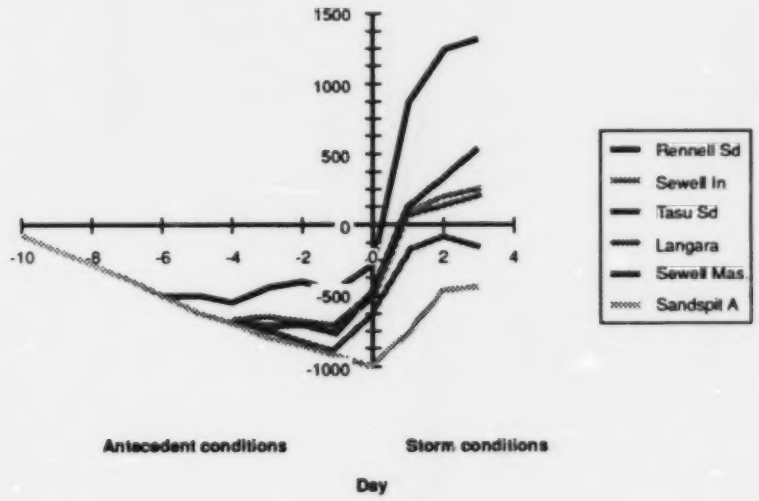


FIGURE 10. Cumulative departure from the daily precipitation: an example of wet and dry antecedent days.

We used these antecedent values to classify the reported slide events according to their wet or dry moisture status (relative to zero), and plotted them with respect to region in Figure 12. The figures show that wet antecedent conditions are more frequently associated with slides in the Masset Inlet, Skidegate Channel and Rennell Sound regions. Dry antecedents are more frequently associated with hillslope failures in the Sewell Inlet and East Moresby regions. What determines these regional differences is not clear. We believe, however, that it is probably due to the relatively high precipitation amounts associated with most individual events in Sewell Inlet and East Moresby compared to those amounts in other regions.

4.4 Summary

A wide range of antecedent moisture conditions "set the stage", or condition the hillslopes for a future failure. All time scales appear to be important, but the short-term (daily) conditions probably have the greatest influence in actually triggering landslides. This leads to several questions:

1. Is there a threshold beyond which landslides occur as a result of excess precipitation?
2. Do smaller amounts of precipitation trigger a slide when the anetecedent conditions are dry, wet or a combination of the two?
3. Does the importance of antecedent conditions depend on storm magnitude? For example, if a large storm occurs, do antecedent conditions matter?

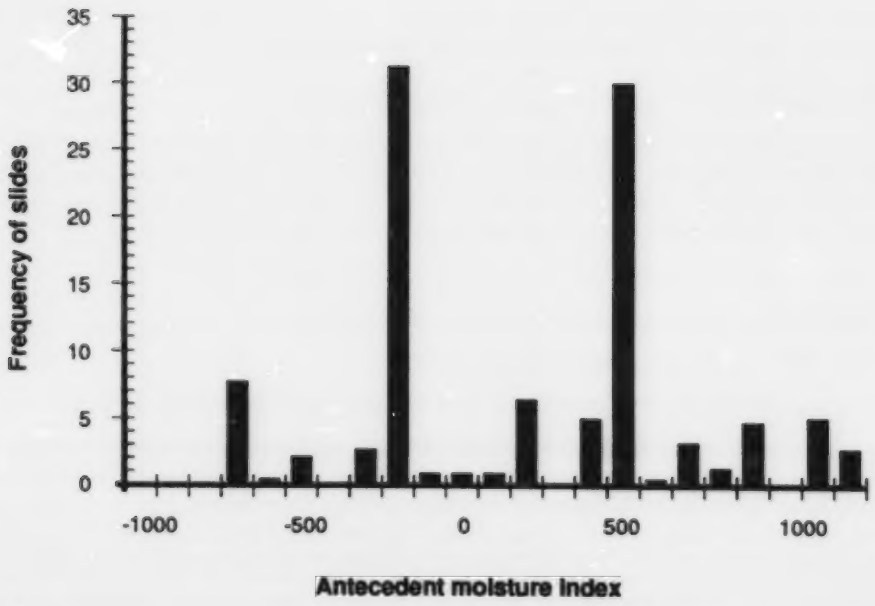


FIGURE 11. Frequency of reported hillslope failures associated with daily moisture status.

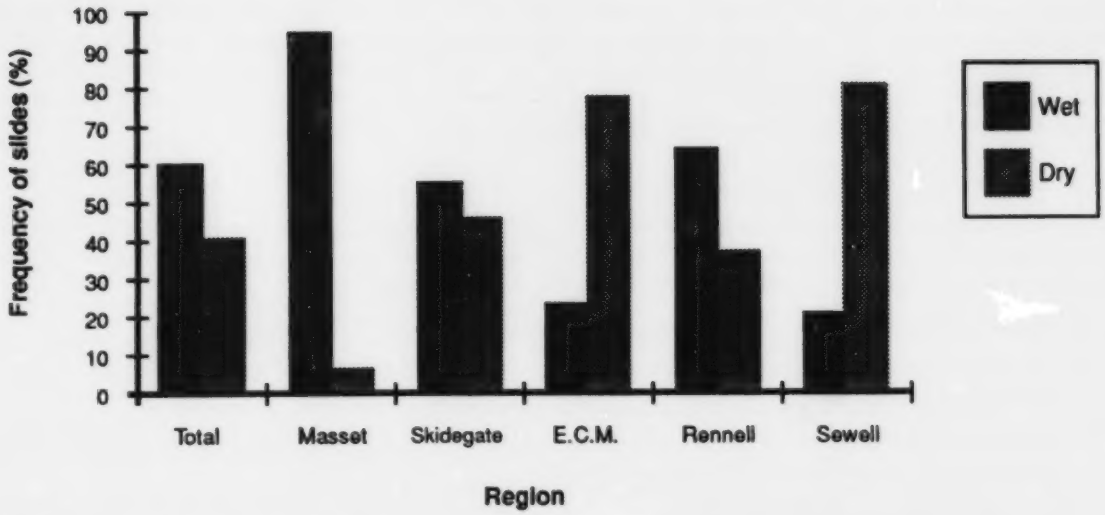


FIGURE 12. Daily antecedent moisture conditions associated with hillslope failures.

5. METEOROLOGICAL CONDITIONS ASSOCIATED WITH SLOPE FAILURES

5.1 Storm Characteristics

Storm events that triggered hillslope failures (Table 1) were plotted as cumulative precipitation curves to show the amount and intensity of precipitation occurring before, during and between storms (Figure 13). The mean intensity values for each storm and the maximum intensity for any 24-hr period were obtained from these curves (see summary on Table 2) and used to determine landslide potential.

5.2 Meteorological Conditions — Hillslope Failure Relationships

The data in Table 2 have been plotted as precipitation amount versus duration to identify the general threshold for slope failures as triggered by precipitation[3]. Our data were grouped into wet and dry antecedent classes and values for each were initially plotted separately. The wet and dry relationships, together with Caine's (1980) and Innes' (1983) relationships, were then summarized (Figure 14).

The relationships shown indicate that the most probable limiting curves[4] are:

$T_w \leq 6.3D^{0.42}$ for wet antecedent moisture conditions; and

$T_d \leq 18.2D^{0.14}$ for dry antecedent moisture conditions;

where: T_w = total precipitation (mm) in period of time with wet antecedent moisture conditions;

T_d = total precipitation (mm) in period of time with dry antecedent moisture conditions; and

D = precipitation duration (hr).

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[3] The limitation with these data are that the shortest duration is determined by AES monitoring procedures (only daily totals available for all stations except Sandspit A). To provide greater temporal resolution, all RAB data for the relevant areas were reviewed. This provided data for durations of 1 hour, which were used with Sandspit A records to define the short duration end of the relationship. RAB records are available for 1977 - 1982 only; stations used are listed in Table 1.

[4] As discussed in Section 2.3, the threshold for hillslope instability is a limiting curve which envelopes all data points with similar characteristics (i.e., wet or dry antecedent meteorological conditions or strictly road-related failures).

TABLE 2. Antecedent moisture classification and storm intensities

Storm No.	Region	Antecedent moisture[a]			Daily cumulative departure index	Average rain intensity (mm/hr)			
		Annual	Monthly	Daily		1 day	2 day	3 day	4 day
22	General	w	c2	d	-760.0	3.97	3.6	2.7	
23	General	w	c2	w	683.6	8.02	7.4	6.58	5.55
24	Skidegate	w	c2	w	778.1	1.9	1.4	1.21	0.91
25	General	w	c2	w	1266.1	6.78	4	0	
26	Skidegate	w	c2	w	778.1	1.28	0	0	
27	Rennell	w	c2	w	2081.5	3.8	3.5	0	
33	East Moresby	w	c2	d	-550.8	6.54	4.8	3.9	
34	East Moresby	w	c2	d	-550.8	6.54	4.8	3.9	
35	Skidegate	w	c1	w	859.3	1.8	1.1	0.87	
36	Masset	w	c1	d	-132.7	0.45	0.4	0.35	
37	Masset	w	c1	w	810.7	0.41	0.3	0	
38	Rennell	w	c4	w	678.2	5.47	3.9	3.25	
39	Masset	w	c4	w	433.9	1.94	1.3	0.93	
40	Skidegate	w	c4	w	1231.8	2.18	1	0.77	
41	East Moresby	d	c2	w	403.7	0.86	0	0	
44	East Moresby	d	c?	d	-686.2	4.47	3.3	0	
42	Rennell	d	c2	w	300.9	5.82	4.8	4.36	
43	Masset	d	c3	w	424.8	2.24	1.6	1.2	
45	East Moresby	d	c1/c2	w	402.2	2.24	2.2	2.01	
49	Sewell	d	c1	d	-292.1	8.46	7.6	5.86	
50	East Moresby	d	c1	d	-292.1	8.46	7.6	5.86	
51	Rennell	d	c1	d	-259.1	2.96	2.8	2.37	
52	Rennell	w(d)	c2	d	-370.5	2.33	2.1	1.8	
53	Rennell	w(d)	c4	d	-58.7	0.27	0	0	
54	Rennell	w(d)	c4	w	-89.6	2.82	2.7	2.04	
55	Rennell	w(d)	c2	d	-314.7	2.27	2.1	1.74	
56	Rennell	w(d)	c2	w	576.3	2.06	1.7	0	
57	Rennell	d(w)	c3	d	-599.6	3.55	0	0	
58	Skidegate	w	c4	d	-285.7	0.53	0.5	0.36	
59	Skidegate	w	c4	d	30.1	2.57	2.1	1.53	
60	Rennell	w	c2	d	-365.1	2.73	2.6	2.21	
61	Skidegate	w	c1	w	2346.2	1.71	0	0	
62	Sewell	w	c1	d	-743.0	4.28	3.8	3.27	
63	Skidegate	w	?	w	1484.8	0.38	0	0	
67	Sewell	-	c2	w	324.2	7.8	7	0	
68	East Moresby	-	c2	w	324.2	7.8	7	0	
69	Rennell	-	c2	w	190.0	3.43	2.8	0	
70	Skidegate	-	c2	d	-203.8	1.65	0.8	0	
71	Masset	-	c2	d	-203.8	1.58	1	0	
73	Skidegate	-	?	w	1363.6	2.18	0	0	
74	Rennell	-	?	w	1108.2	0	0	0	
75	East Moresby	-	?	w	804.6	2.99	0	0	
76	Masset	-	?	w	417.3	0	0	0	

[a] Annual conditions are "w" for wet or "d" for dry, relative to the long-term normal precipitation amount. Monthly classes (c1, c2, c3, c4) refer to Figure 9.

Therefore, under wet conditions when $T_w \leq 6.3D^{0.28}$, hillslope failure is unlikely. Under dry conditions, slope failure will probably not occur if $T_d \leq 18.2D^{0.14}$ when storm durations are less than 3 days. However, if a storm lasts longer than 2-3 days, then the antecedent conditions begin to resemble those of wet conditions; the T_d and T_w lines merge at this point. There are several points in Figure 14 that lie below the limiting curves. These points are from road-related failures that are due more to inadequate road drainage than to precipitation intensity or duration.

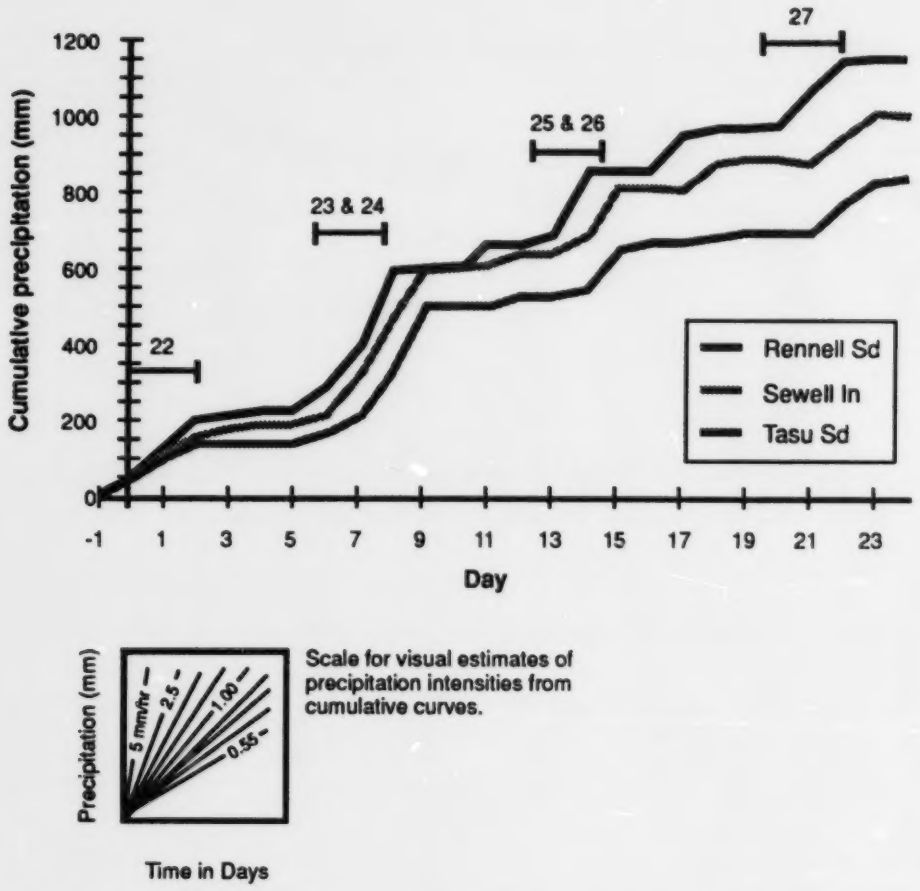


FIGURE 13. Cumulative daily precipitation for selected storms. Horizontal bars with numbers refer to storm events listed in Table 1.

The Queen Charlottes' data seem to compare favourably with the relationships developed by Caine (1980) and Innes (1983) where $T \leq = 14.82D^{0.61}$ and $T \leq 4.94D^{0.5041}$, respectively. The wet antecedent condition relationship is similar to Innes', although the slope of the graph for the Queen Charlottes' data is less. This suggests that, in our study, as storm duration increases, less precipitation is required to trigger hillslope failures than was found in the Innes study, which did not consider antecedent moisture conditions but did specify failure type (35 debris flows). Caine's limiting curve, located in the middle of our data, over-estimates the amount of precipitation required to trigger slope failures on the Queen Charlottes. Caine's relationship has a slightly steeper slope and a higher intercept compared to those in the Queen Charlotte Islands relationships.

The apparent merging of the wet and dry limiting curves indicate the storm magnitude beyond which antecedent moisture conditions are of reduced importance to slope failure (Figure 14). That is, the difference between the wet and dry limiting curves represents the storm recurrence interval required before antecedent conditions become unimportant. The difference in precipitation is approximately 12 mm over a 1-hr period, 7 mm over 24 hours, and 3 mm over 48 hours. Return interval data for precipitation events of 24-hr duration are presented in Figure 15. Comparing data from Figures 14 and 15 shows that storms with recurrence intervals of greater than 2 years can trigger slope failure regardless of the antecedent moisture status. This is important because many of the slope failures on the Queen Charlottes occur during low magnitude-high frequency precipitation events. This also seems to confirm that antecedent moisture conditions associated with the small but frequent storm events are important.

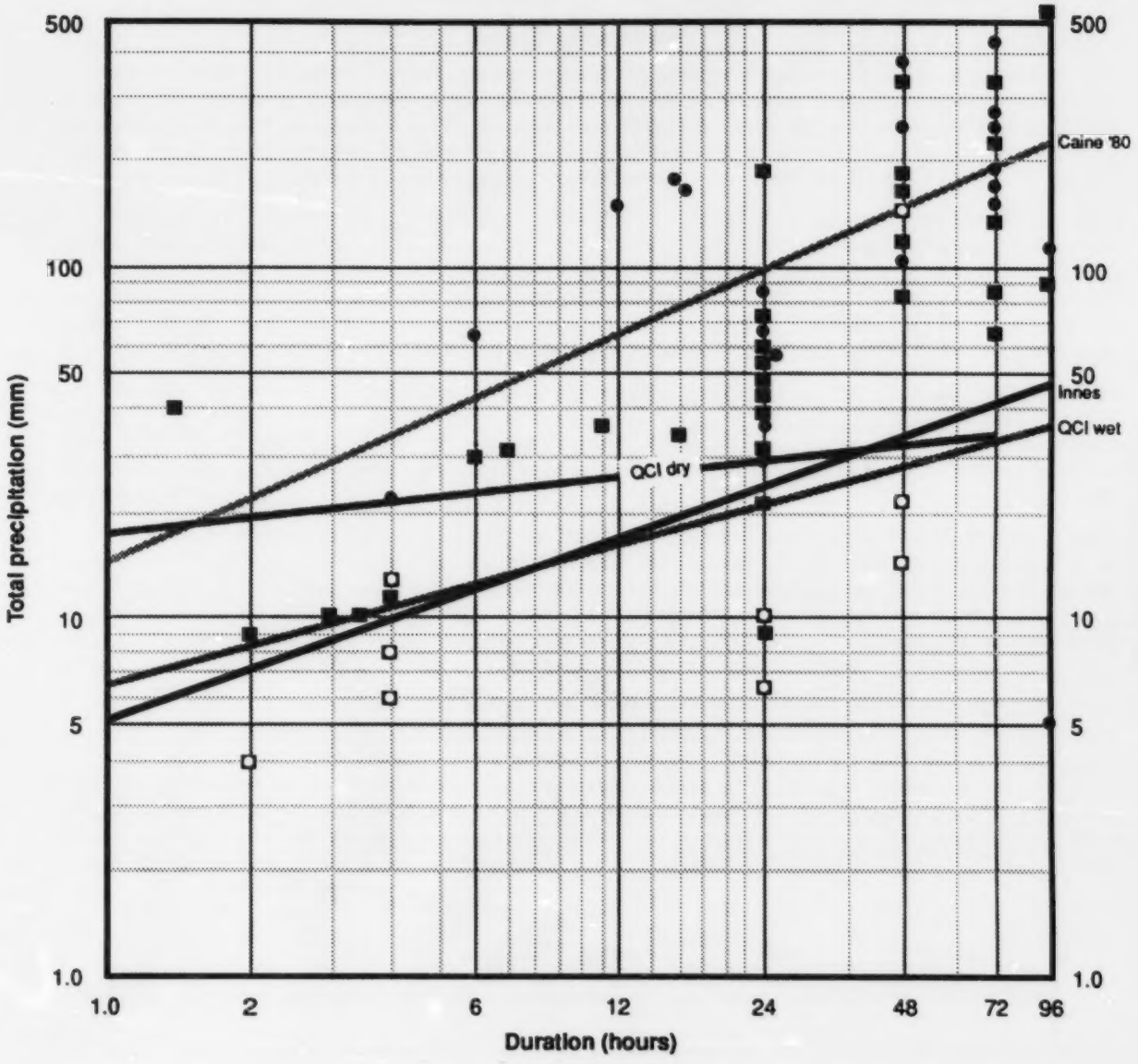


FIGURE 14. Scattergram illustrating the precipitation amount - duration relationship for reported hillslope failures.

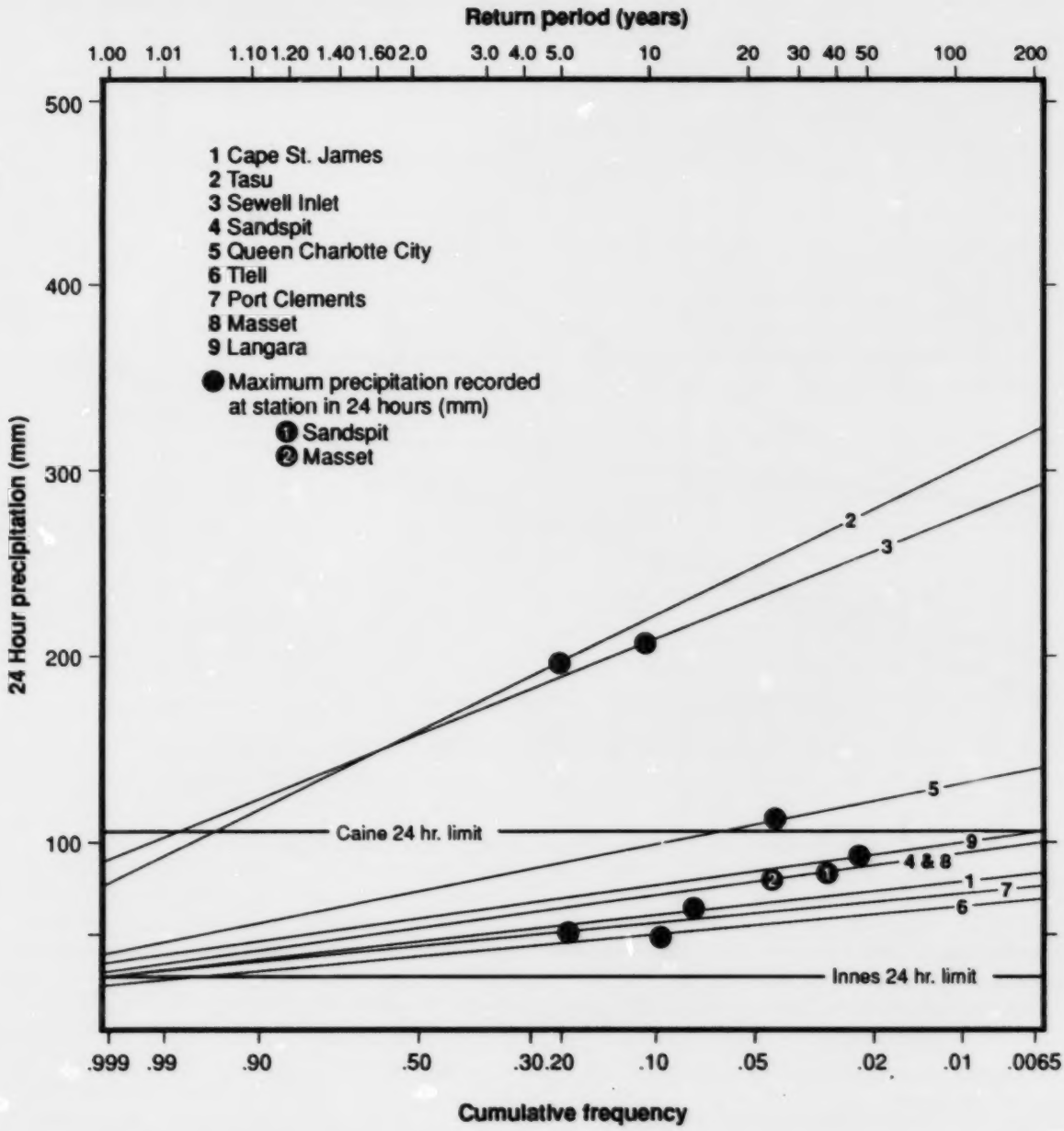


FIGURE 15. Precipitation (24-hr totals) recurrence intervals (from Hogan and Schwab 1990).

It is not possible to incorporate storm magnitude information directly into the precipitation duration intensity and slope failure relationships as presented in Figure 14. However, by plotting the degree of wetness or dryness against storm intensity, we can combine storm magnitude with the antecedent moisture condition and slope failure relationship (Figure 16). Storm duration is restricted to 24-hr precipitation totals. This is a limitation, but most weather stations provide data in 24-hr format only (making this is an important operational restriction). Figure 16 shows that as the previous 10 days become drier, the storm required to trigger a slope failure becomes proportionally larger. A storm return interval of between 2 and 10 years is necessary before antecedent moisture conditions become relatively unimportant.

Figure 16 also indicates precipitation amounts required to trigger slope failures in the Queen Charlotte Islands. This provides a "baseline" by which actual and estimated slope failure events can be compared. To do this, all available AES records were reviewed to determine the frequency of storms with 24-hr total precipitation amounts exceeding 25 mm and 100 mm. The lower value is close to that indicated in Figure 14 as the threshold for slope failures to occur under wet antecedent conditions; the higher value represents rare events at locations other than west coast sites (Figure 15). Slope failures are probable under these high precipitation conditions.

Precipitation values required to trigger hillslope failures are exceeded on a regular basis in all regions of the Queen Charlotte Islands and in every month of the year (Figure 17). Although the frequency of such events is higher within the Rennell Sound and East Moresby regions, they do occur in every month in the drier Masset Inlet and Skidegate Channel areas. Winter months experience the most frequent occurrence of these threshold precipitation amounts.

Variability is evident on an annual basis, but 24-hr precipitation events exceeding 25 mm have been experienced in every year of record (Figure 17b). The AES records from 1974 to 1983 are plotted in Figure 17 so that the data can be compared to the available landslide occurrence data from the Queen Charlotte Islands (Figure 18; the entire AES record was used to calculate average frequency per year by month). Comparing Figures 17 and 18 shows that there are many occasions when precipitation levels are sufficient to trigger slope failures, but actual failures either did not occur or were not observed and recorded.

Many reasons may account for the absence of slides during periods with 24-hr precipitation levels of 25 mm or more, but antecedent conditions do appear to be important, particularly during the low magnitude-high frequency events. From a management perspective, precipitation levels are sufficient to trigger slope failures year round in all steep land locations on the Islands. Although logging and related activities were not explicitly considered here, slopes failed at precipitation levels far lower than the T_d determined for the Queen Charlottes (Figures 14 and 16; note points below the limiting curves and labelled as road-related failures). Such failures are probably due to local site conditions and site modification from forest harvesting activities.

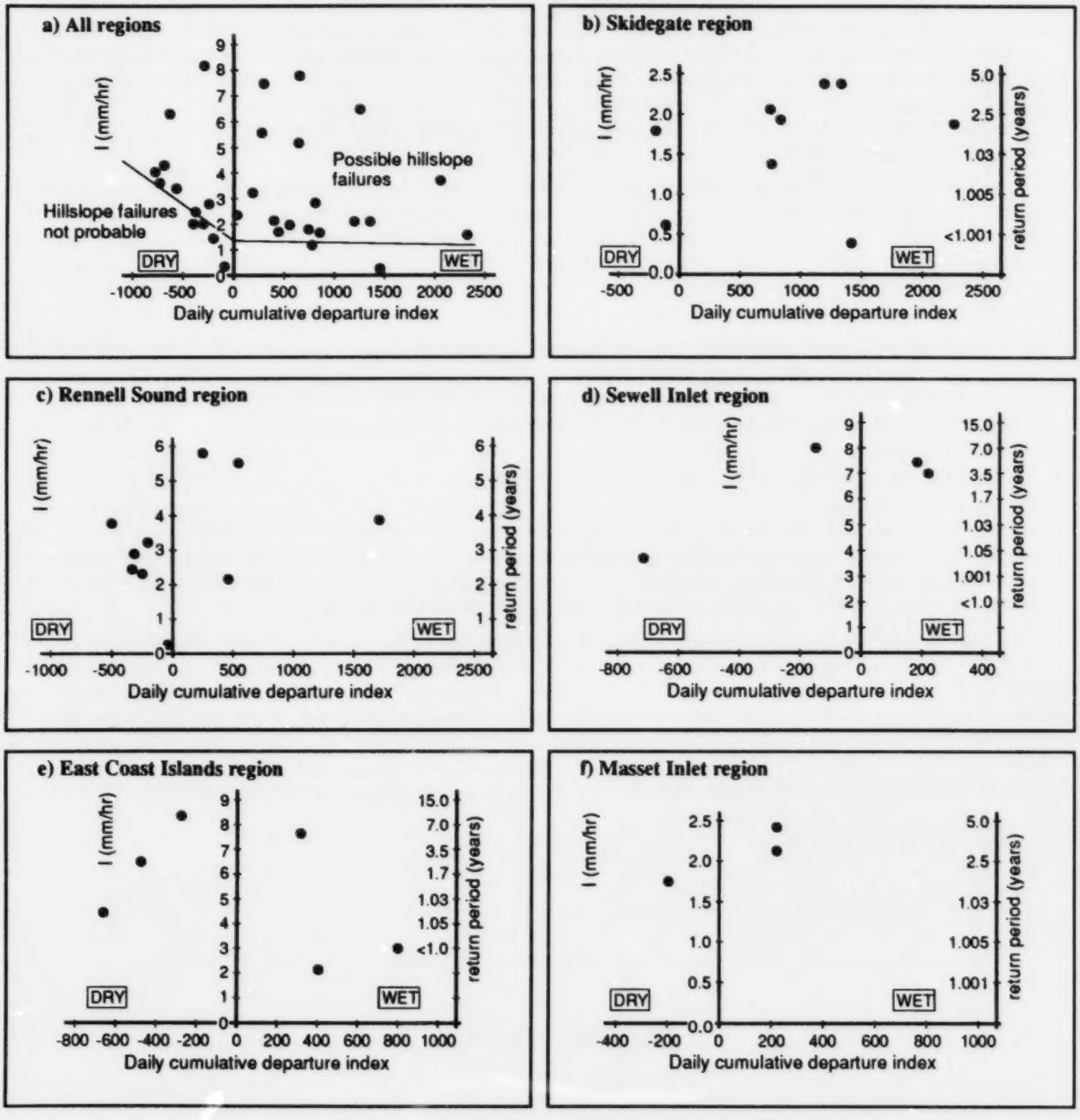


FIGURE 16. Hillslope failure occurrence associated with antecedent moisture index. Precipitation intensity (I) is based on 24-hr totals. To obtain total precipitation for comparison with Figure 14, multiply I by 24.

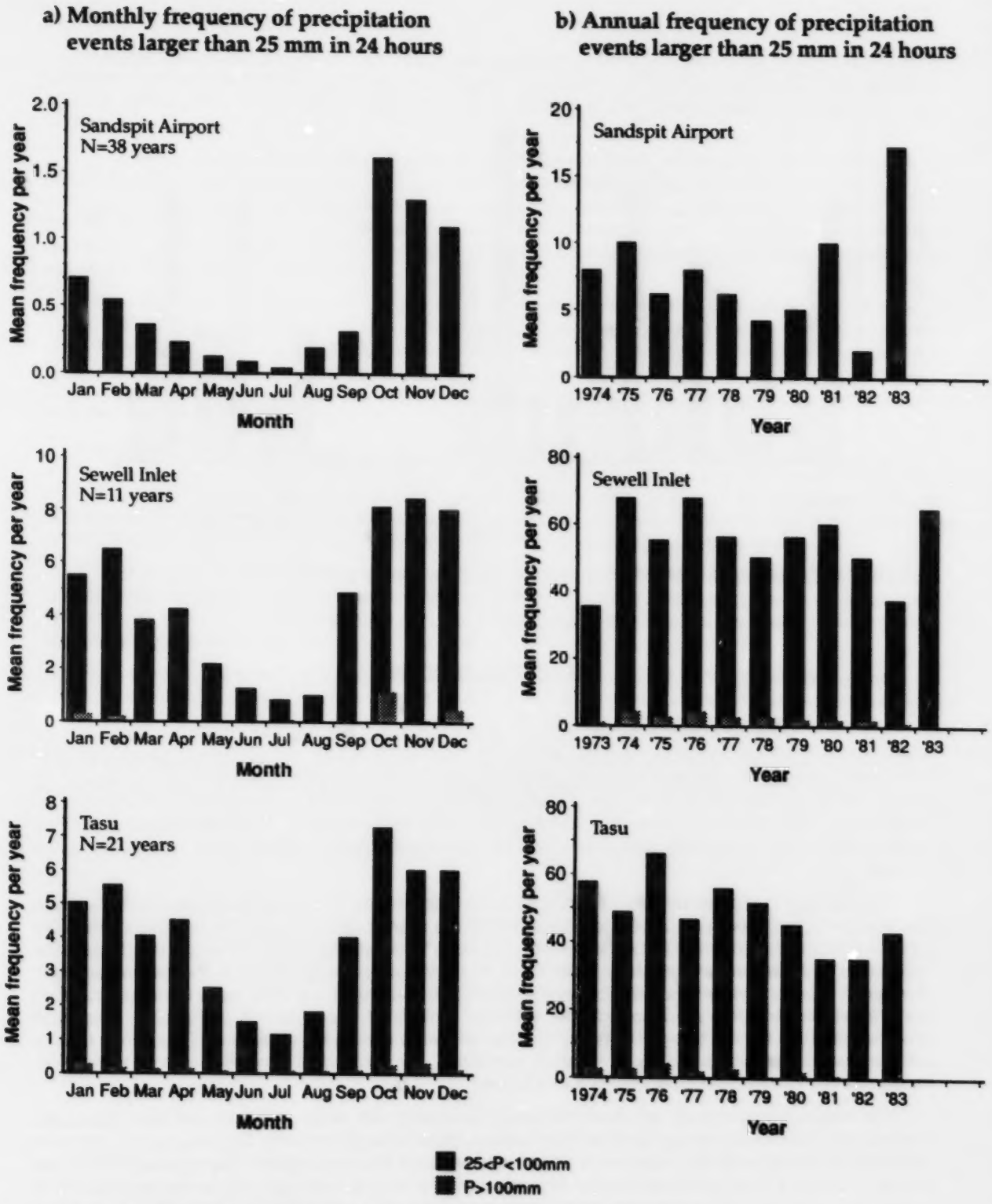

a) Monthly frequency of precipitation events larger than 25 mm in 24 hours
b) Annual frequency of precipitation events larger than 25 mm in 24 hours
Sandspit Airport
N=38 years
Sewell Inlet
N=11 years
Tasu
N=21 years
Mean frequency per year
Month
Year
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
1974 '75 '76 '77 '78 '79 '80 '81 '82 '83
1973 '74 '75 '76 '77 '78 '79 '80 '81 '82 '83
25<P<100mm
P>100mm

FIGURE 17. Frequency of precipitation events larger than 25 mm in 24 hours.

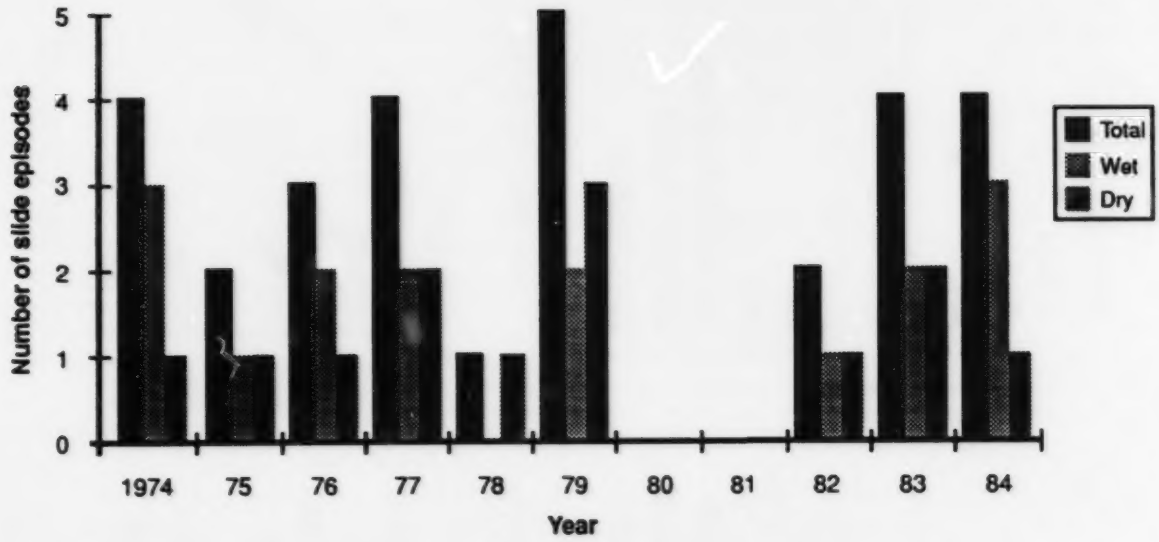


FIGURE 18. Frequency of reported slope failures by antecedent moisture condition.

6. CONCLUSIONS

There is an apparent pattern between annual moisture conditions and reported slope failure frequency: as annual precipitation increased, the average number of slides increased as well. However, there are periods during which lower than average precipitation levels resulted in a high number of failures (e.g., 1975-1977), as well as shorter periods with relatively high precipitation levels corresponding to low frequency of failures (e.g., 1980-1981). These results are somewhat complicated by the forest industry's changing awareness of hillslope failures, differences in reporting procedures, and the increased amount of steep-slope logging during the 1970's.

The distribution of slope failures on a monthly basis indicates that the annual moisture conditions are of less relevance to the occurrence of slope failures than are shorter time periods. The antecedent moisture conditions of only those months immediately before the slope failure are important; the annual trend masks the importance of the winter months. Many slides occur as a result of relatively moderate precipitation amounts received after prolonged periods of dry (below normal precipitation) conditions. Also, many failures occur when low precipitation amounts are received after extended periods of above normal precipitation. The most important situation leading to high frequency of slope failures is continual wet weather. Thus, slope failures occur in association with a variety of moisture conditions, but antecedent conditions appear to be most important in conditioning the hillslopes for future failures.

Wet antecedent conditions are more frequently associated with slides in the Masset Inlet, Skidegate Channel and Rennell Sound regions than in the other regions selected for study. Dry antecedents are more frequently associated with slope failures in Sewell Inlet and East Moresby regions. The reason for this is not evident, although it is possible that the East Moresby locations receive fewer days with moderate amounts of rainfall. The relatively high rainfall days are therefore more frequently associated with slope failures.

Hillslope failures occur under a wide range of antecedent moisture conditions: dry years and wet years experience slides. Monthly moisture conditions appear to condition the hillslope for failure. Daily conditions probably influence how important variable amounts of short-term precipitation can be in triggering slope failures.

Calculations of the minimum precipitation required to initiate hillslope failures on the Queen Charlotte Islands showed that hillslope failures have not occurred where the total amount of precipitation received in any 24-hr period, following a prolonged wet period, is less than 22 mm. More precipitation is required to trigger slides under dry conditions. Failures may occur where total precipitation exceeds 29 mm in 24 hours for storm durations of less than 3 days. If a storm lasts longer than 2 days, then the antecedent conditions (2 days before a slide) begin to resemble wet conditions.

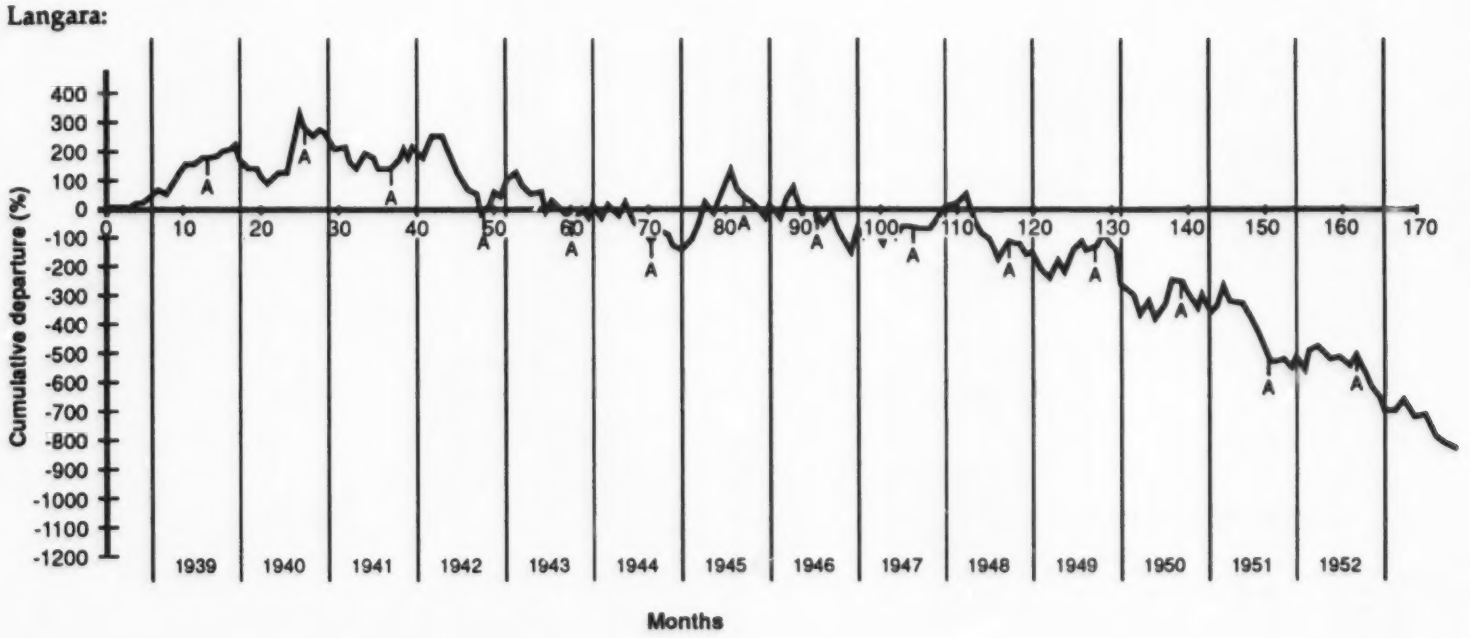
The relationships in the Queen Charlotte Islands have some similarity to those developed for other areas (Caine 1980; Innes 1983). The wet antecedent condition relationship is similar to that of Innes, although the slope of the Queen Charlottes curve is slightly less. This indicates that more precipitation is required over very short durations and that as storm duration increases, less precipitation is required to trigger slope failures. Caine's limiting curve plots in the middle of the Queen Charlotte Islands data appears to over-estimate the minimum amount of precipitation required to trigger slope failures on the Islands.

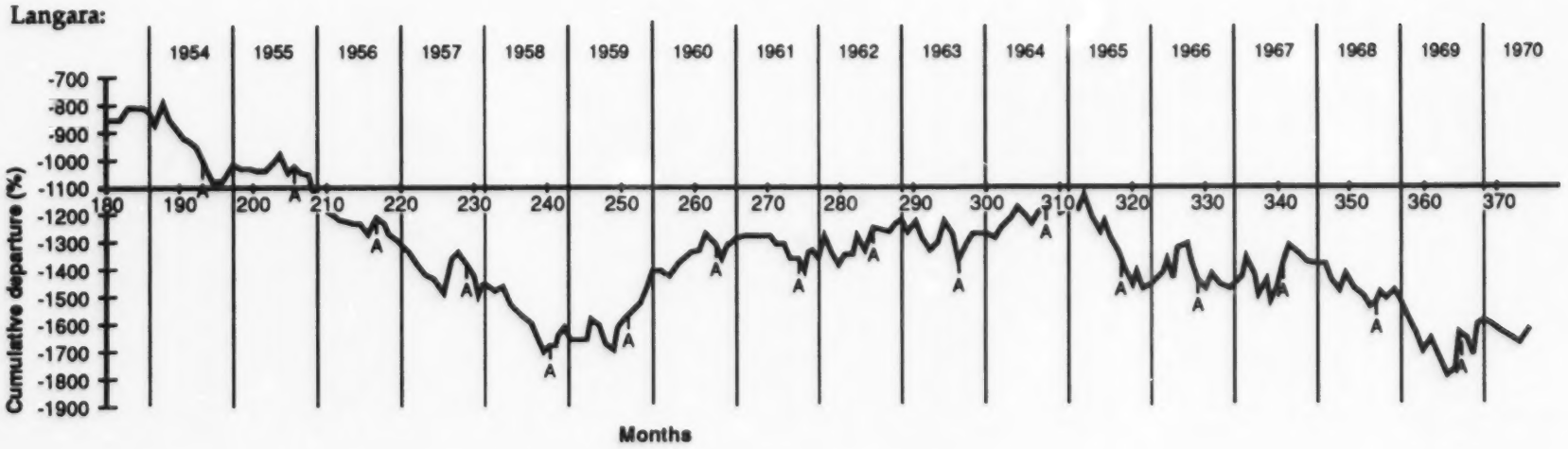
The separation between limiting curves associated with wet and dry antecedent moisture conditions represents the size of storm or amount of precipitation required before antecedent conditions become unimportant to slope failure occurrence. Storms with recurrence intervals of greater than 2 years may trigger failures regardless of antecedent moisture status. This is important because many of the slope failures on the Queen Charlotte Islands occur during the low magnitude-high frequency precipitation events.

Precipitation levels are generally sufficient to trigger slope failures at all times and in all areas of the Queen Charlotte Islands. Many reasons may account for the absence of slope failures during periods when precipitation levels exceed 25 mm, but antecedent conditions do appear to be important, particularly during the low magnitude-high frequency storms.

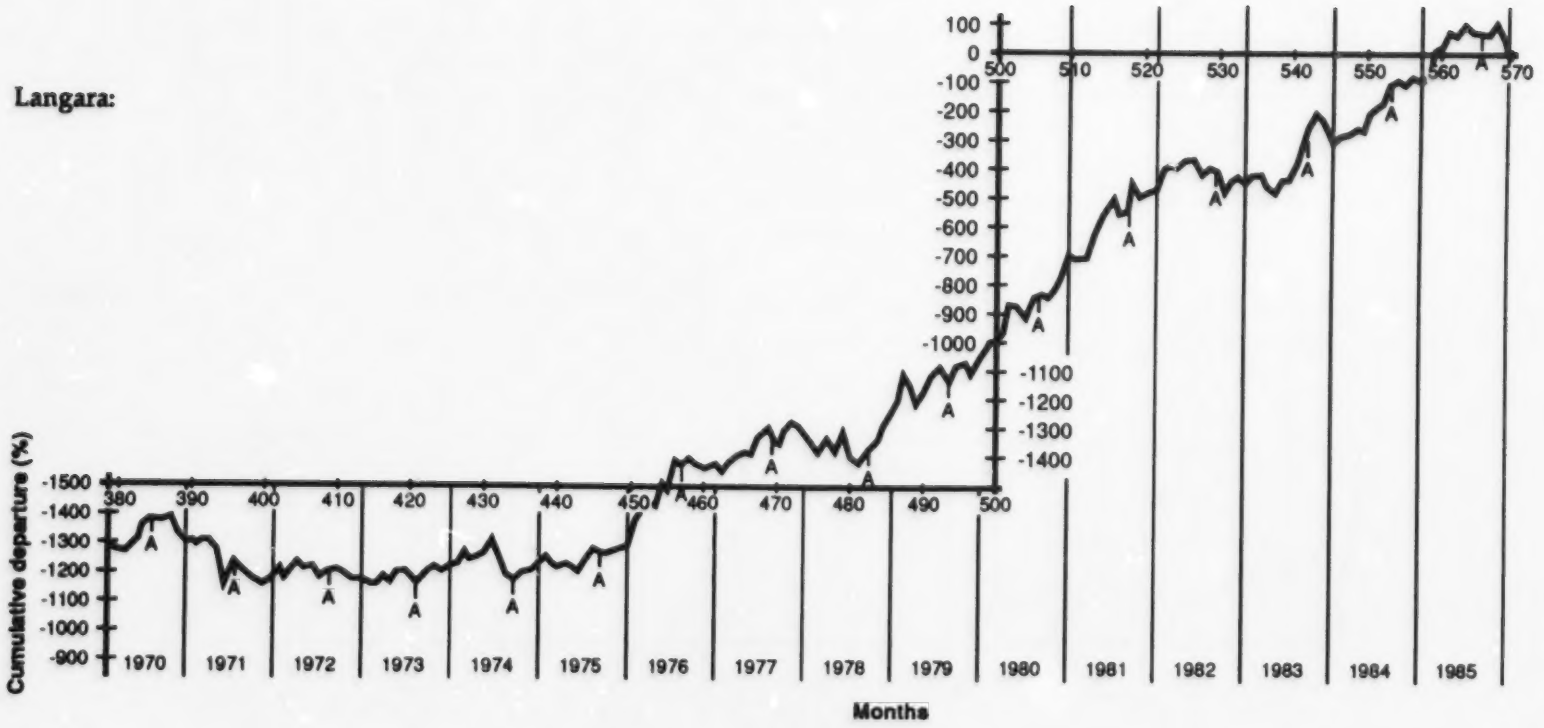
From a forest management perspective, precipitation values required to trigger hillslope failures are exceeded regularly in all regions on the Queen Charlotte Islands, though the threshold values are exceeded most frequently during the winter months. The "moderate storm", or low magnitude-high frequency event (2 - 10 year return interval) must therefore be taken into consideration in harvesting layout, road design, and road maintenance in potentially unstable terrain. Harvesting activity plans must also recognize that failures can even occur at much lower levels of precipitation because of local site and soil moisture conditions.

APPENDIX 1. Cumulative precipitation plots for monthly records from 1963 to 1983



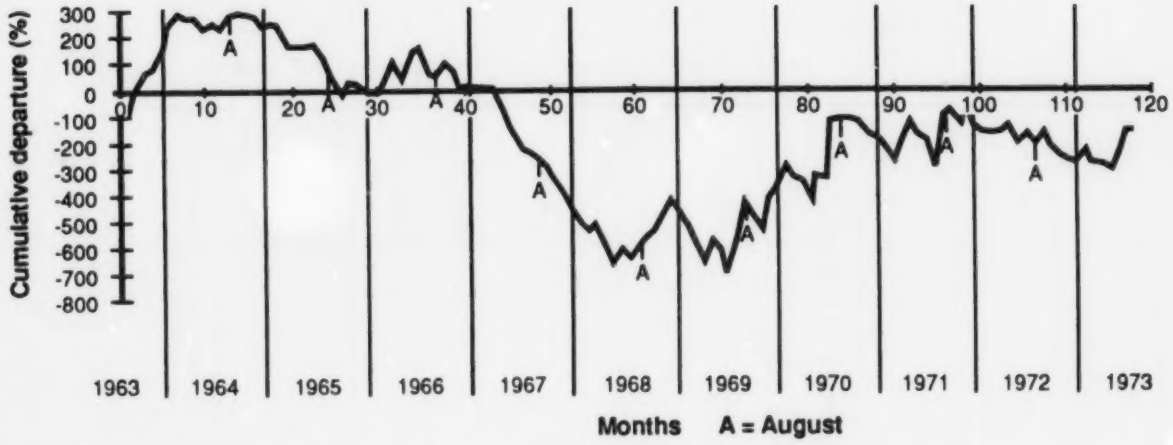


APPENDIX 1. Continued



APPENDIX 1. Continued

Tasu:



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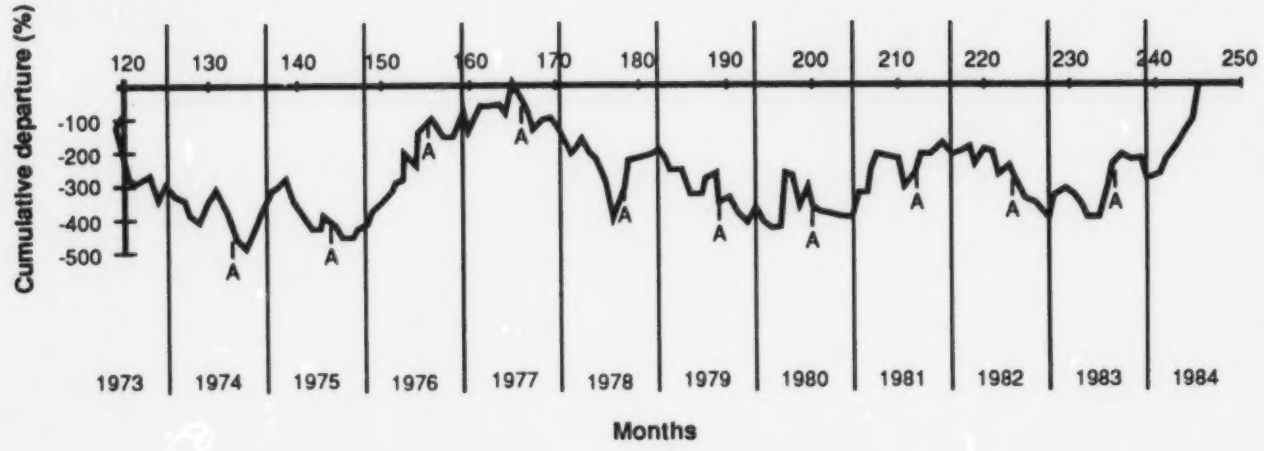
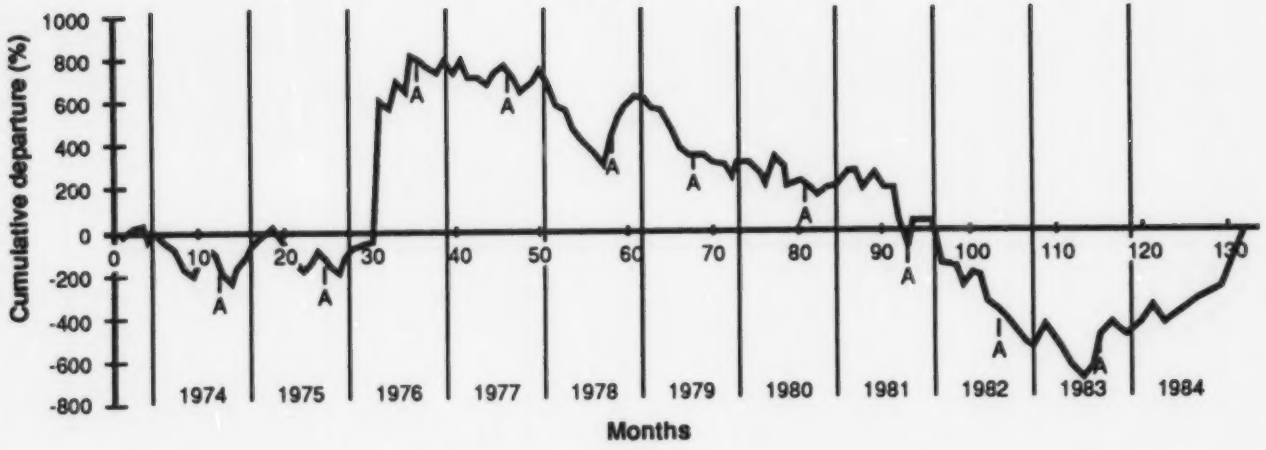
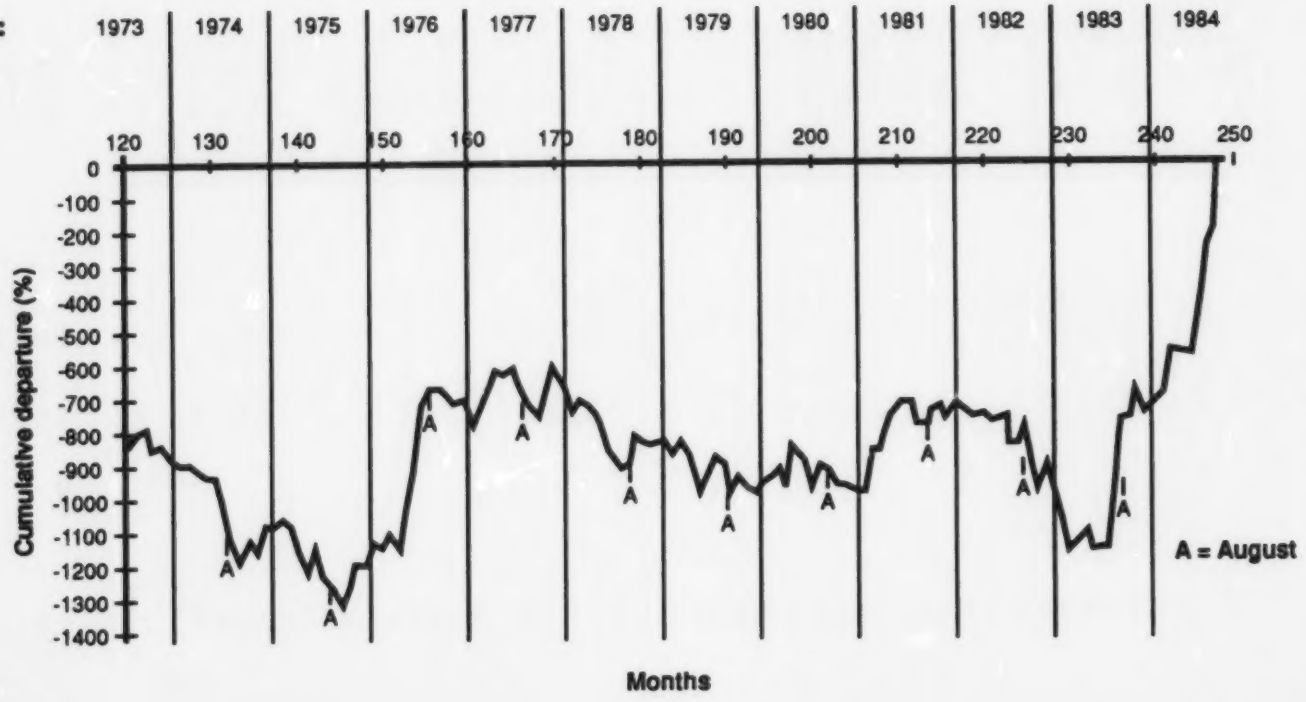


APPENDIX 1. Continued

Sewell Inlet:



Sandspit:



APPENDIX 2. Summary of reported hillslope failures by time of occurrence and geographic location

No.	Date			Slope Failure Location[a]	Minimum Frequency[b]	Notes
	Year	Month	Day			
21	1974			Skidegate	1	
22		Sept 30-Oct 2		General	*	
23		Oct	6-8	General	*	
24		Oct	9	Skidegate	3	Road
25		Oct	13-14	General	*	
26		Oct	15	Skidegate	1	
27		Oct	21-22	Rennell	1	
28	1975			Skidegate	2	
29		Mar-May		Masset	2	Road
30		Oct	2-6	Masset	1	Road
31		Oct	16	Masset	1	Clearcut
32		Oct	24	Skidegate	1	
33		Oct	24	East Moresby	1	
34		Nov	2	East Moresby	2	
35		Nov	17	Skidegate	1	
36	1976	Jun	6	Masset	2	Road
37		Sep	10	Masset	1	Road
38		Nov	1-3	Rennell	1	
39				Masset	13	Road
40		Nov	3	Skidegate	1	
41	1977	Feb	28	East Moresby	2	
42		Oct	21-26	Rennell	1	
43		Oct	23-28	Masset	1	
44		Oct	10	East Moresby	1	
45		Nov	9	East Moresby	4	
46	1978			Sewell	2	
47				Skidegate	8	
48				Rennell	3	
49		Oct 29-Nov 1		Sewell	21	
50				East Moresby	42	Gullies, road
51				Rennell	113	Forest
51				Rennell	151	Clearcut/roads
52	1979	Sep	28	Rennell	2	
53		Oct	29	Rennell	1	
54		Nov	19	Rennell	1	Logging
55		Dec	4	Rennell	2	
56		Dec	25	Rennell	1	
57	1982	Jan	28	Rennell	2	Logging
58		Oct	8	Skidegate	1	Clearcut
59	1983	Jan	23	Skidegate	2	Windthrow
60		Jan	23	Rennell	1	Clearcut
61		Aug	2	Skidegate	3	
62		Sep	23	Sewell	13	12 logging
63		Oct	14	Skidegate	1	
64		Oct	27	East Moresby	1	
65		Nov	3	East Moresby	26	
66		Nov	11	East Moresby	3	

APPENDIX 2. Continued

No.	Date			Slope Failure Location[a]	Minimum Frequency[b]	Notes
	Year	Month	Day			
67	1984	Jan	25	Sewell	11	9 clearcut
68		Jan	25	East Moresby	6	Forest
69		Jan	25	Rennell	13	clearcut
70		Jan	25	Skidegate	7	6 logging
71		Jan	25	Masset	2	
		Jan	25	General	100	
72		Feb	10	East Moresby	25	10 Forest 15 Road
73		Oct	12	Skidegate	2	
74		Oct	12	Rennell	1	
75		Oct	12	East Moresby	7	
76		Oct	13	Masset	49	Clearcuts
77		Oct	22	East Moresby	44	2-Forest

Notes: [a] Location; refer to Table 2. and Figure 1.

[b] Minimum frequency refers to the observed and reported numbers of slope failures; in some situations, many more slides are thought to have occurred but the actual date has not been verified. For instance, the Forest Service estimated that 100-150 slides occurred Queen Charlotte-wide during the Jan. 25, 1984 storm whereas only 39 were recorded. The "*" indicates that many slides occurred but that records were not compiled.

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